Simulating the Large Synoptic Survey Telescope (LSST) One Photon at a Time

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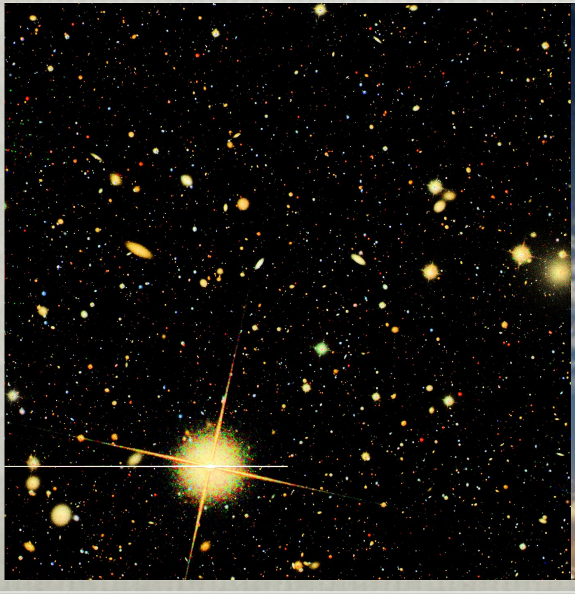
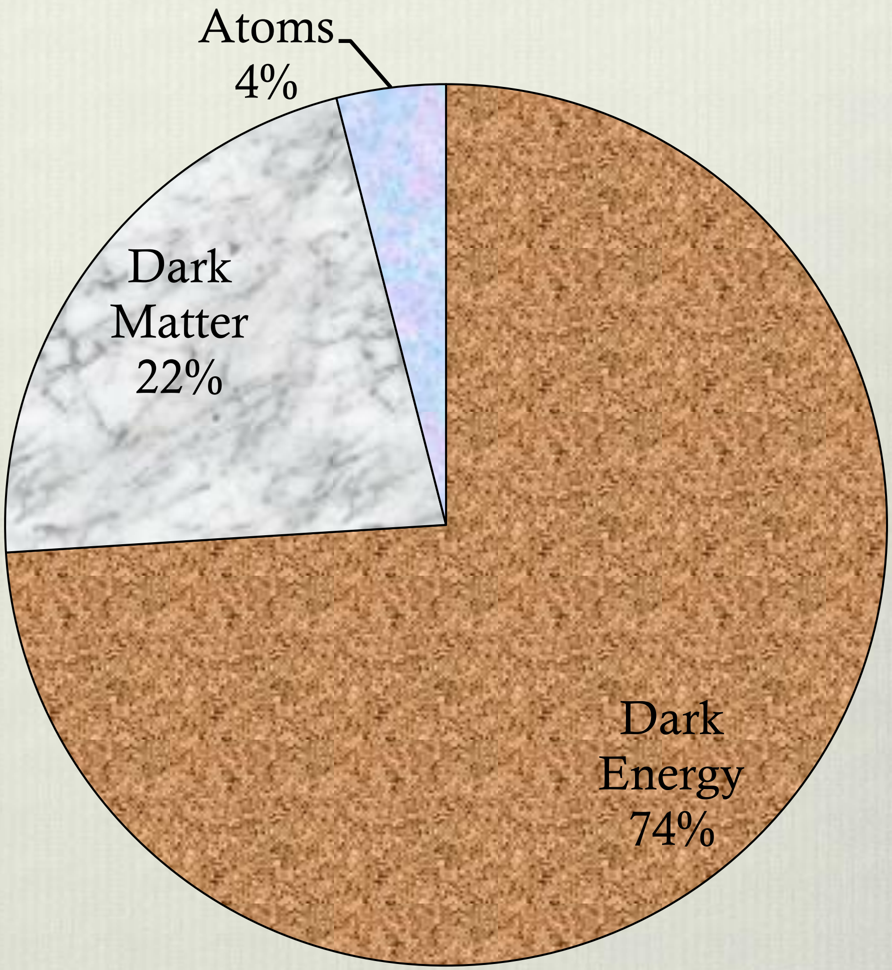
& the LSST Collaboration & the LSST DESC Collaboration



Modern Cosmology

- Most measurements have suggested a Universe of mostly dark energy, some dark matter, and little baryon filled Universe
- CMB ~ total content: few % within critical
- Clusters ~ DM/atoms ratio is ~6
- Supernovae~DE dominant in expansion
- BBN ~ small fraction of atoms

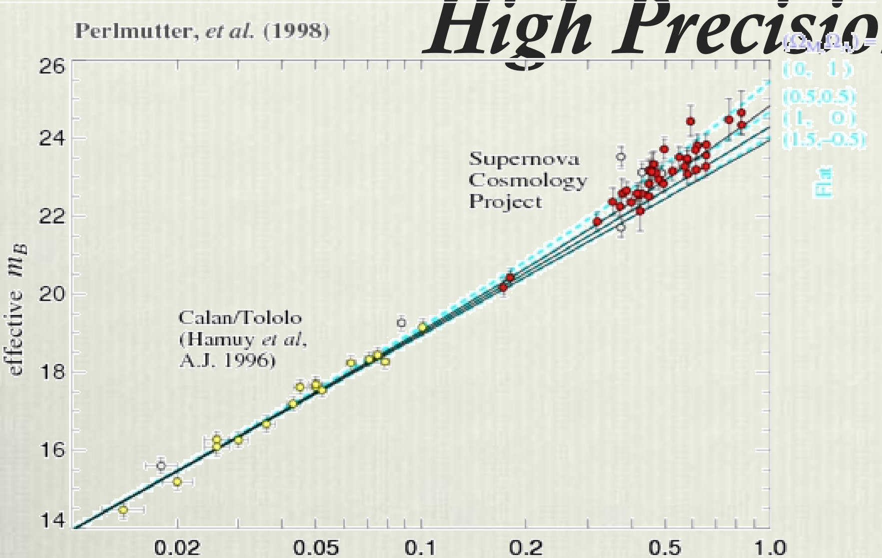


Is this even right? 96% of the Universe is beyond the Standard Model. What is the consequence of this? What can we measure about these further?

Future Measurements in Cosmology

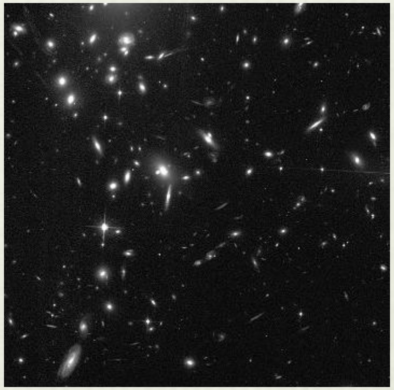
- Need more data to get higher statistical precision
- Need multiple astrophysical techniques
- However, when you push towards higher statistical precision have new systematics that need to be understood
- And with a large enough quantity of data & high enough precision would need both fast and high fidelity simulations to understand these details

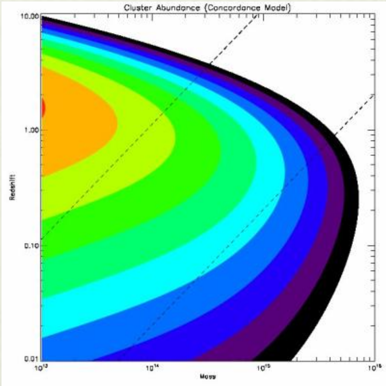
High Precision Cosmological Techniques



1) SNe to Measure Expansion Rate

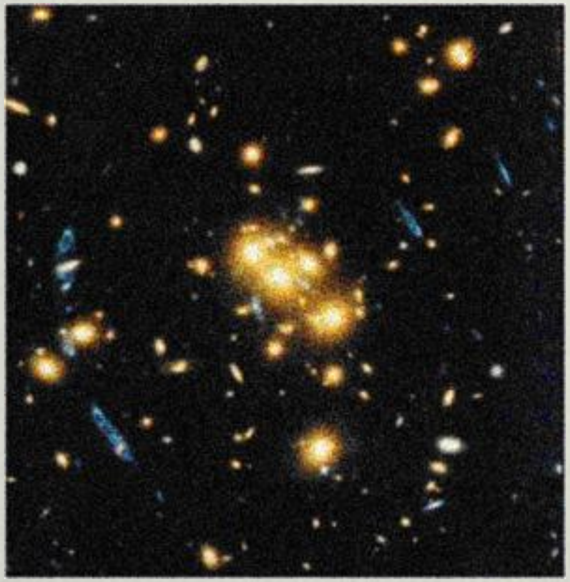
(Perlmutter 1998; Reiss 1998)





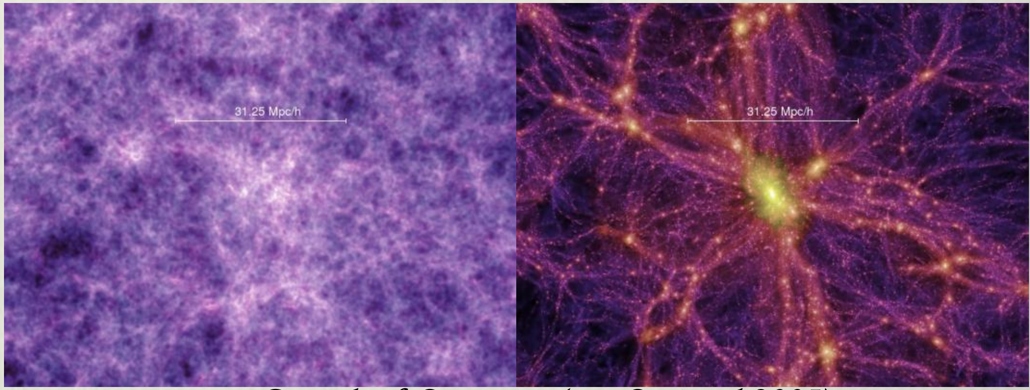
3) Cluster Mass Function Evolution

(Vikhlinin 2009; JRP 2012)

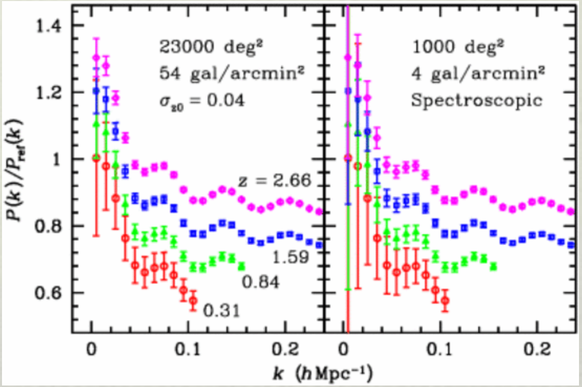


2) Time delays in strong lens images

(Suyu 2010)



Growth of Structure (e.g. Springel 2005)

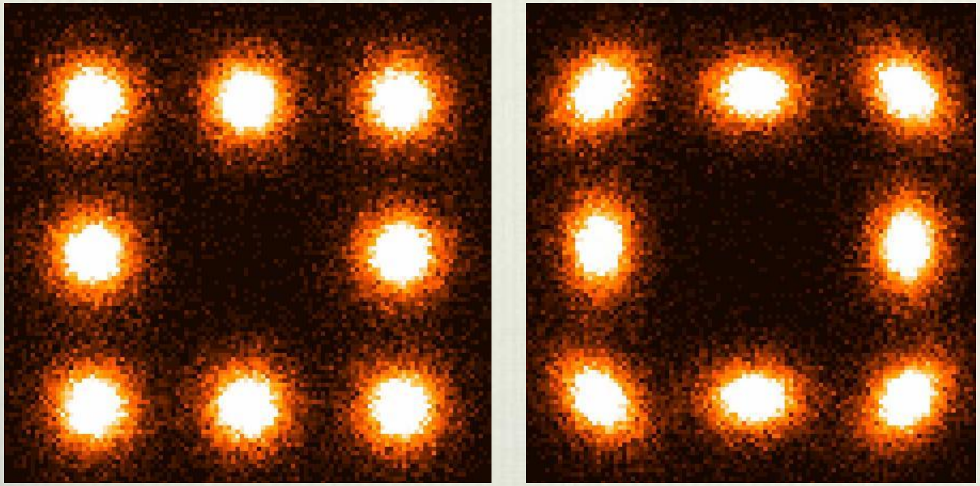


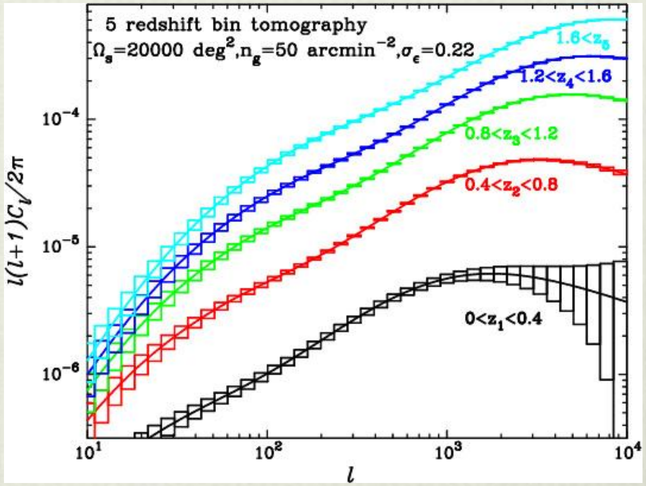
4) Baryon Acoustic Oscillations in Matter Power Spectrum

(Eisenstein 2005)

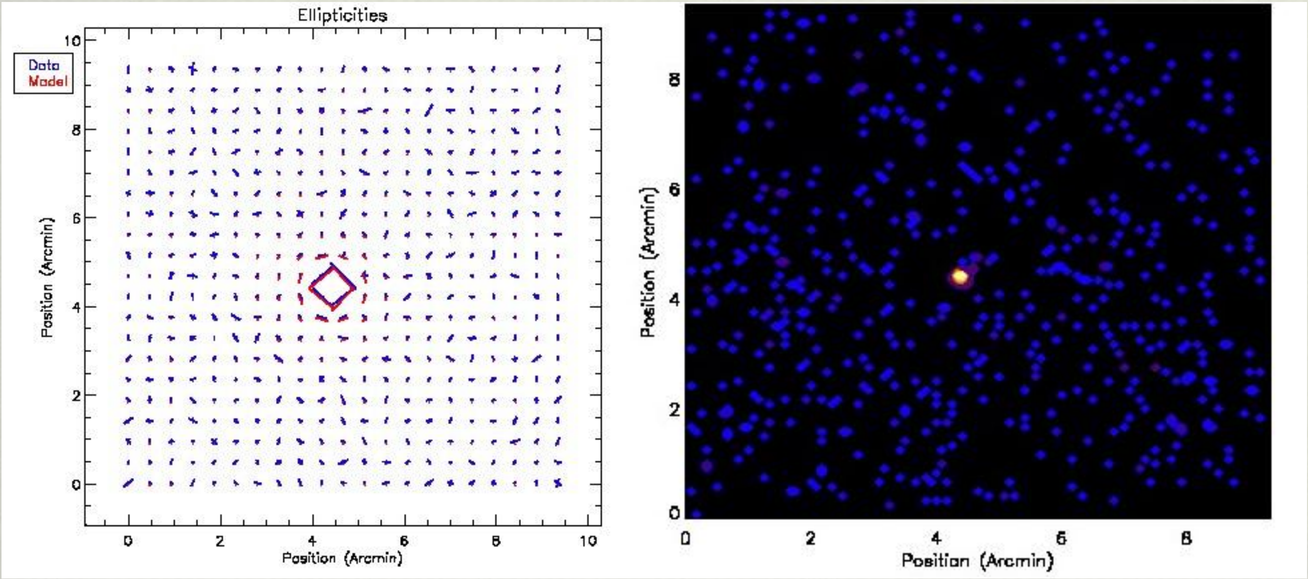
High Precision Cosmological Techniques

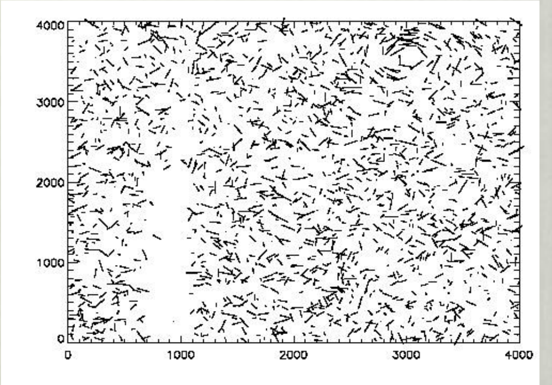
5) Weak Gravitational Lensing



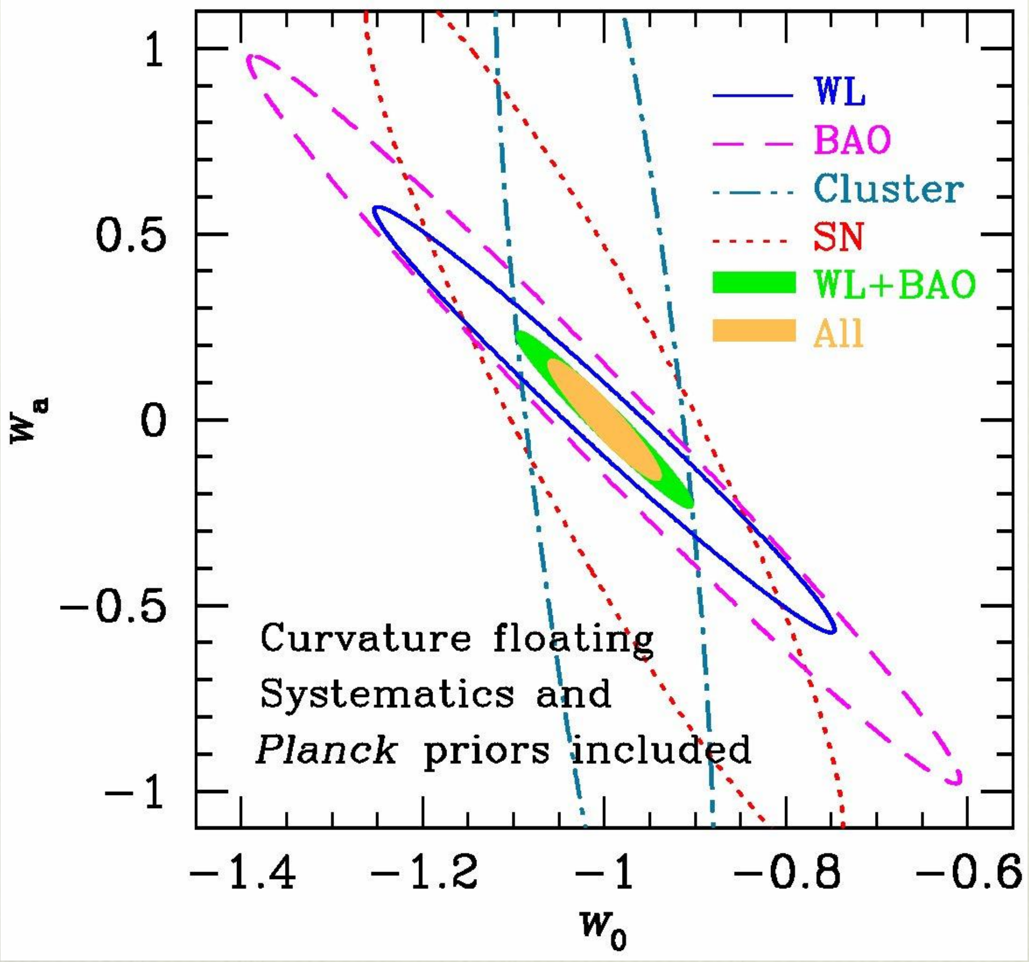


Knox et. al 2004





High Precision Cosmological Techniques



Hu 2008

Dark Energy Constraints

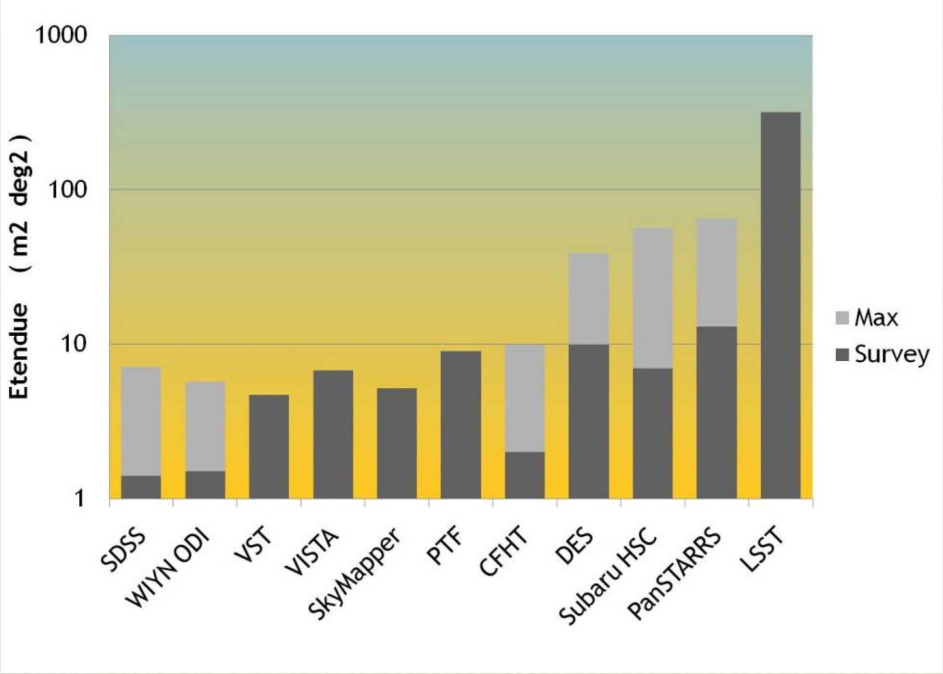
Will have increasing discriminatory power to distinguish between cosmological constant and various models

LSST will measure:

- 3 billion galaxies
- 10 billion stars
- 1 million SNe
- 10,000 clusters
- Dark Matter Map of Entire Sky

[Also the other major area requiring high precision is stellar astrometry where large Fraction of milky way will be mapped with proper motions & some parallaxes]

How does LSST do this? Etendue



Etendue is the product of
Area and Field of View

To get more area simply build
a large telescope

To get higher field of view, favor
designs with shorter focal lengths,
and minimal vignetting, reasonable
off-axis image quality

Consequence of this is have to
build a large camera

Consequence of a large camera is
large data rate

Large Synoptic Survey Telescope (LSST)

Adler Planetarium, Brookhaven National Laboratory (BNL), California Institute of Technology, Carnegie Mellon University, Chile, Cornell University, Drexel University, Fermi National Accelerator Laboratory, George Mason University, Google, Inc., Harvard-Smithsonian Center for Astrophysics, Institut de Physique Nucleaire et de Physique des Particules (IN2P3), Johns Hopkins University, Stanford University, Las Cumbres Observatory Global Telescope Network, Inc., Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), National Optical Astronomy Observatory, Princeton University, Purdue University, Research Corporation for Science Advancement, Rutgers University, SLAC National Accelerator Laboratory, Space Telescope Science Institute, Texas A & M University, The Pennsylvania State University, University of Arizona, University of California at Davis, University of California at Irvine, University of Illinois at Urbana-Champaign, University of Michigan, University of Pennsylvania, University of Pittsburgh, University of Washington, Vanderbilt University

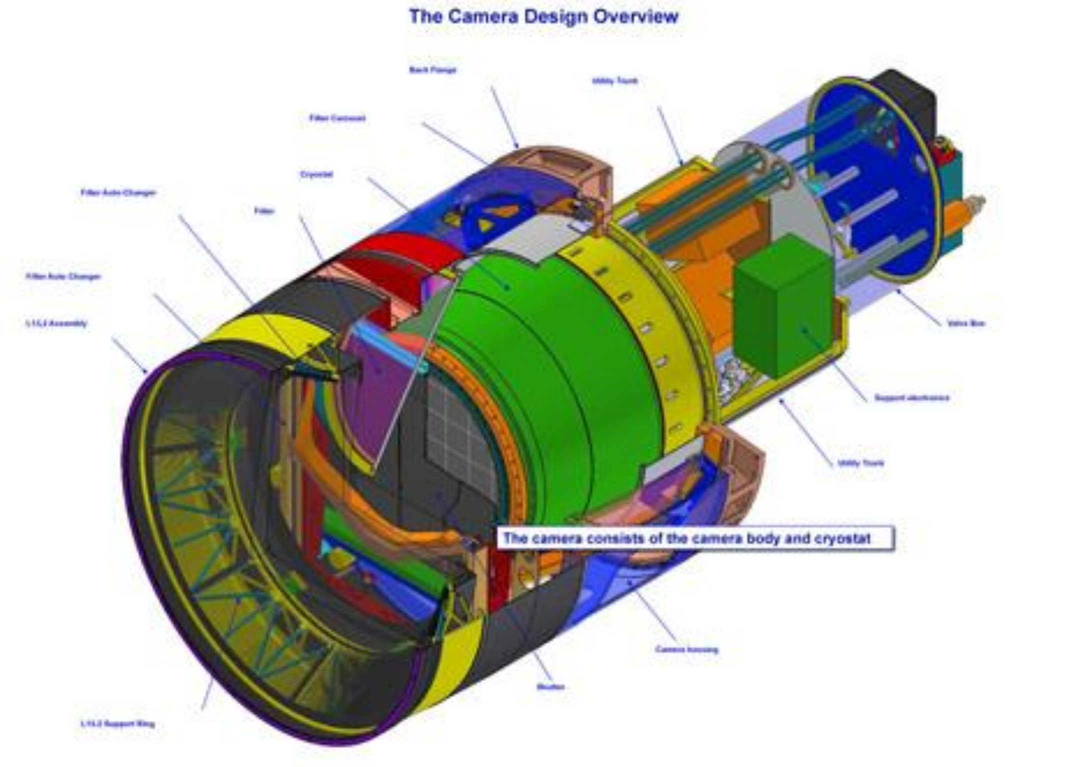
www.lsst.org

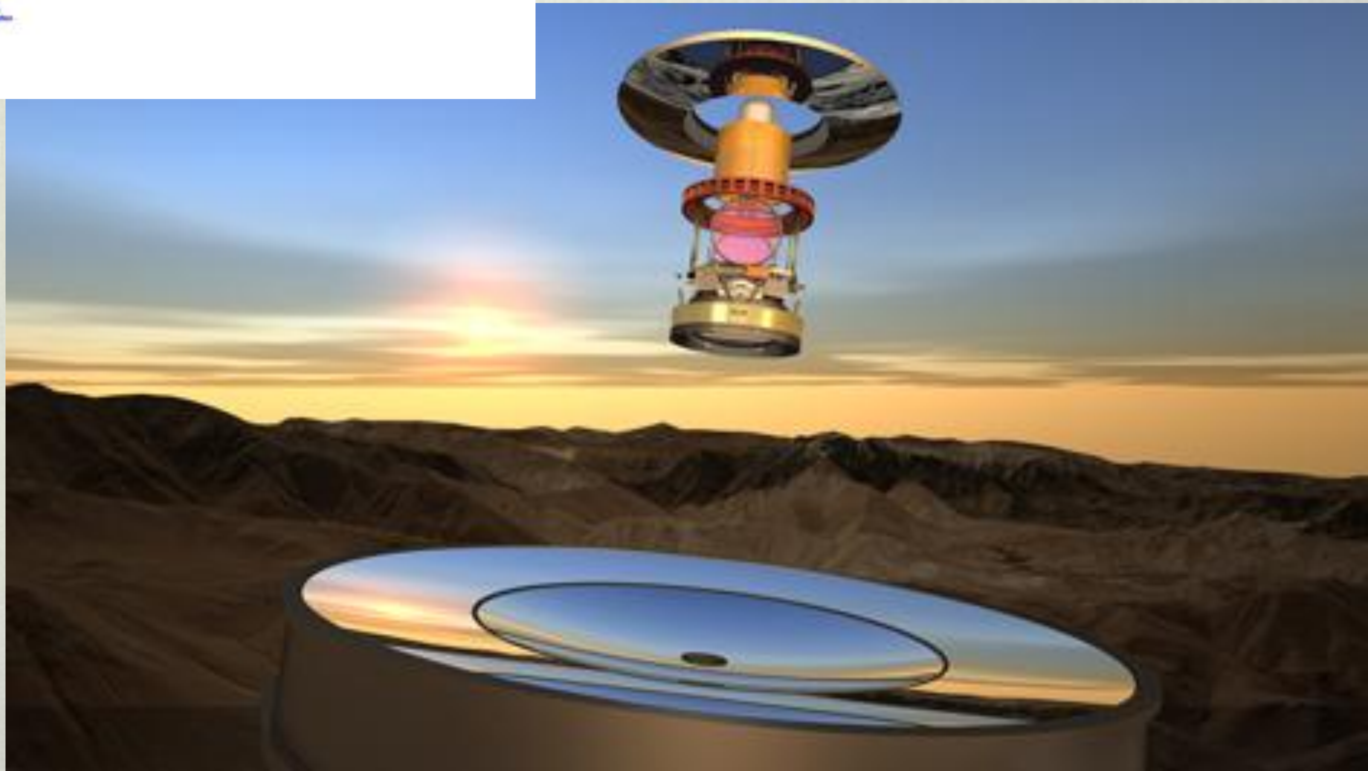
- Largest survey telescope: Highest Etendue (area*FOV) for a telescope: 320 m^2deg^2
- Largest data rate 10Tb/night!
- 8.4 m mirror; 6 filters (300-1100 nm)
- Largest Astronomical Camera
- Joint NSF & DoE project
- Commissioning in ~2019;
- First science observations in ~2021
- Surveys the ½ the sky every few nights
- Get ~1000 images in 6 colors over 10 years to ~27 mag of everything (billions of galaxies & stars, & all asteroids >150 m, rare objects)

LSST Site

LSST Mirrors

LSST Camera

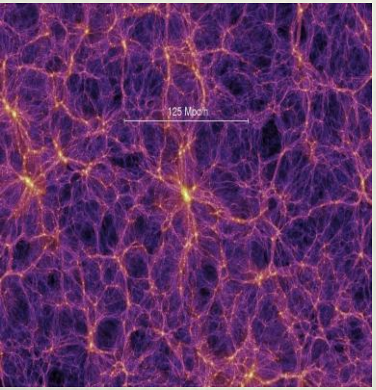

The Camera Design Overview
The camera consists of the camera body and cryostat



Importance of Simulations for LSST

- ❖ More data than any other astronomical project
- ❖ Produces 3 gigapixel images (~1500 HDTV's) every 15 seconds
- ❖ No one can ever look at all the data ➔ Automatic processing (that has to work when telescope turns on)
- ❖ In addition, some of the most accurate measurements ever made have been planned especially for cosmology
- ❖ ➔ Maybe we should do some simulations
- ❖ Have led development of a novel photon simulation (phoSim) code for several years in the LSST project

DESC Simulation & Analysis Framework



object 0.002 -
2.439485 14.5
galaxySED/Const64e
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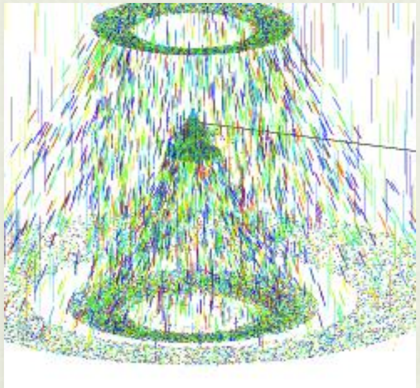
2.980 ccm 2.3 8.2
ccm 2.78 9.45



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Universe → Catalogs → Photons → Images → Measurements

COSMO-LOGICAL SIMULATOR: Synthetic Universe is constructed

CATALOG CONSTRUCTOR (CATSIM): Universe is parameterized in catalogs that can later be photon sampled

PHOTON SIMULATOR (PHOSIM): Atmosphere, Telescope, & Camera physics formulated in terms of photon manipulations

DATA MANAGEMENT (DM) & DESC LEVEL-3 ANALYSIS: Image processing to produce catalogs and measurements on the catalogs

Image Simulations (IMSIM)=PHOSIM+CATSIM

Image Properties

- First order image properties
  - Photometric zeropoint
  - Background level
  - PSF size
  - Astrometric scale

Some existing simulators (Sky Maker (Bertin), Shapelets (Dobke), GalFast (Mandelbaum), DES (Lin)) use parametric models to capture some image properties

To get detailed second image properties have to go to full photon Monte Carlo approach

Essentially all DE measurements depend on some combination of detailed PSF size/shape, astrometry, or photometry

- Second Order Image properties
  - PSF size wavelength dependence
  - PSF size spatial dependence
  - PSF size spatial variation
  - PSF shape (ellipticity and other moments)
  - PSF wings
  - PSF shape wavelength-dependence
  - PSF shape spatial decorrelation
  - PSF shape spatial variation
  - Differential astrometric non-linearity
  - Differential astrometric wavelength-dependence
  - Differential astrometric decorrelation
  - Photometric chromaticity
  - Photometric variation in time
  - Background spatial dependence
  - Background spatial variation
  - Background wavelength dependence

  And more…

Optical Photon Monte Carlo Simulations

Physics of PhoSim

Sky:

Observing configuration from OpSim
Photon Monte Carlo for Galaxies (elliptical Sersic bulge/disk), Stars, Asteroids (moves during & between exposures)
Dust absorption at source & Milky Way
Separate SEDs for every object
Instance Catalogs to include other objects
Background of blank sky, moon, twilight, inc. gradients

Atmosphere:

Multi-layer multi-scale frozen Kolmogorov screens
Outer scale model
Seasonal Wind model for LSST site
Turbulence vs. height model for LSST site
Atmospheric raytrace (refractive turbulence & optical depth)
Atmospheric dispersion
Atmospheric molecular opacity (wavelength, height, & time dependent)
Multi-level grey cloud model

Optics & Detector:

Reflection/Refraction in optics/detector
Diffraction
LSST Optics Design (filter-dependent)
Focal plane layout
Two-level Spider design
Alt/Az Tracking Errors, Rotation Jitter, Spider rotation
Dome Seeing
Surface Perturbations & Alignment errors of mirrors/lenses/detectors
Large Angle Scattering
Angle-dependent filter curves
Lens coatings
Mirror Reflectivity
Saturation & Blooming
Detector A/R
QE & Charge diffusion model
Cosmic rays
Read Noise, Dark Current, Gain, Pre-scans, Offsets for amplifiers
Hot pixels/columns & dead pixels
Non-uniform QE Maps
CTE
Biases/Darks/Flats
Complete Optimization for saturation, background, photon removal, & non-sequential rays

Very important physics

- PSF size, shape, & astrometry (*where the photon lands*)
  - Optical Design
  - Perturbations/Misalignments
  - Charge Diffusion
  - Turbulence
- Photometry (*how many photons*)
  - Geometric design
  - Rayleigh scattering
  - Filter multi-layer coatings
  - Photo-electric conversion

Regimes of Image Simulation

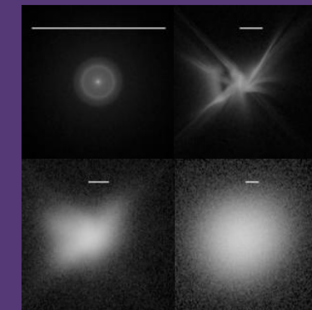
$D >> r_0 \sim 10$ cm

Aberrations+Diffusion $>> \lambda(f/\#)$

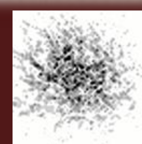
$D << r_0 \sim 10$ cm

★ Modern Survey Telescopes

Elliptical or More Complex PSF (Geometric Optics)



$D >> r_0 \sim 10$cm



Speckle Pattern (Numerical FT)

Elliptical PSF (Geometric Optics)

Aberrations+Diffusion $<< \lambda(f/\#)$

★ Modern AO Telescopes

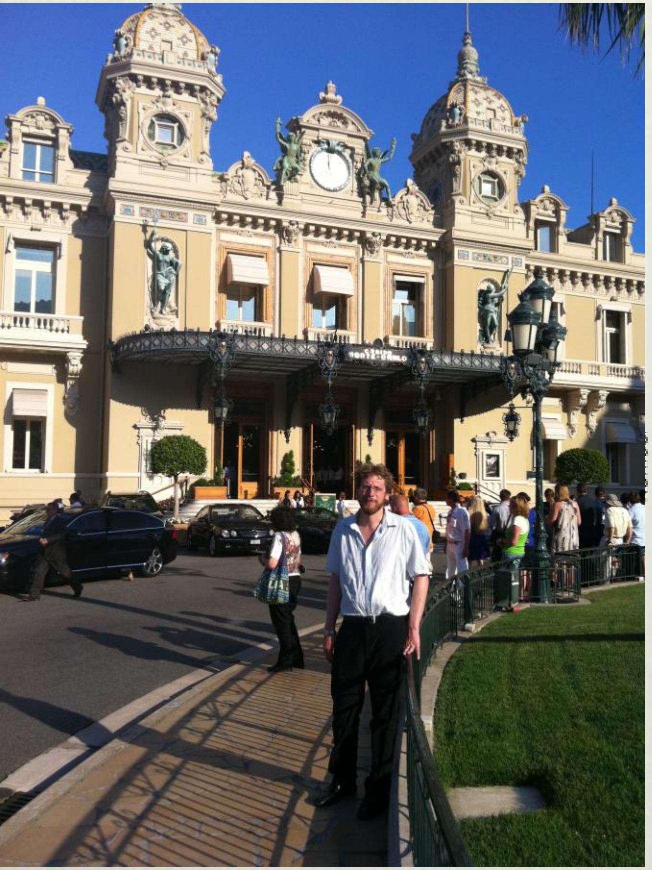
$D << r_0 \sim 10$ cm or adaptive optics

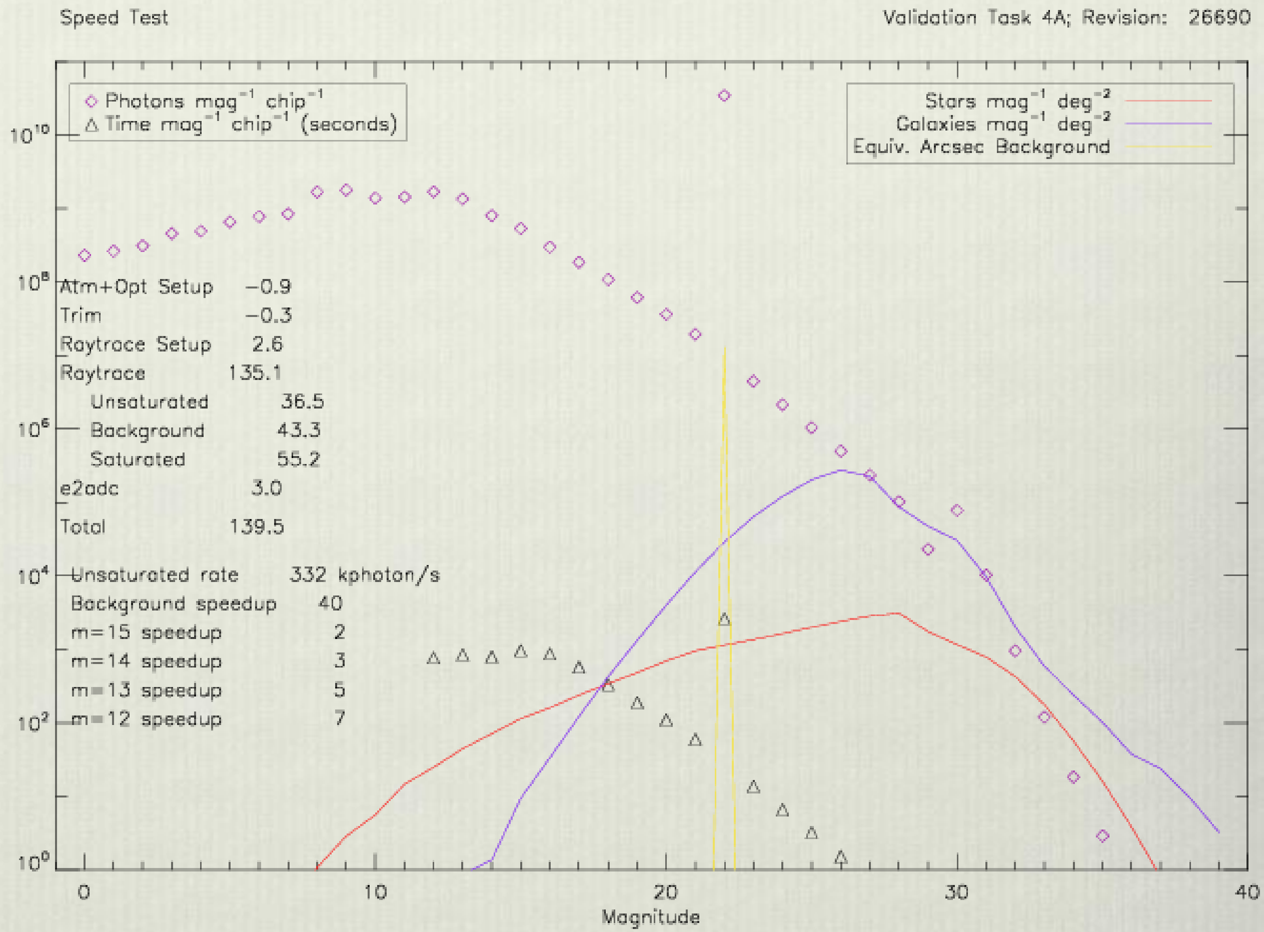
Airy-like Pattern (Numerical FT)

$t_{exp} << D/v \sim .1$s

$t_{exp} >> D/v \sim .1$s

Monte Carlo Efficiency

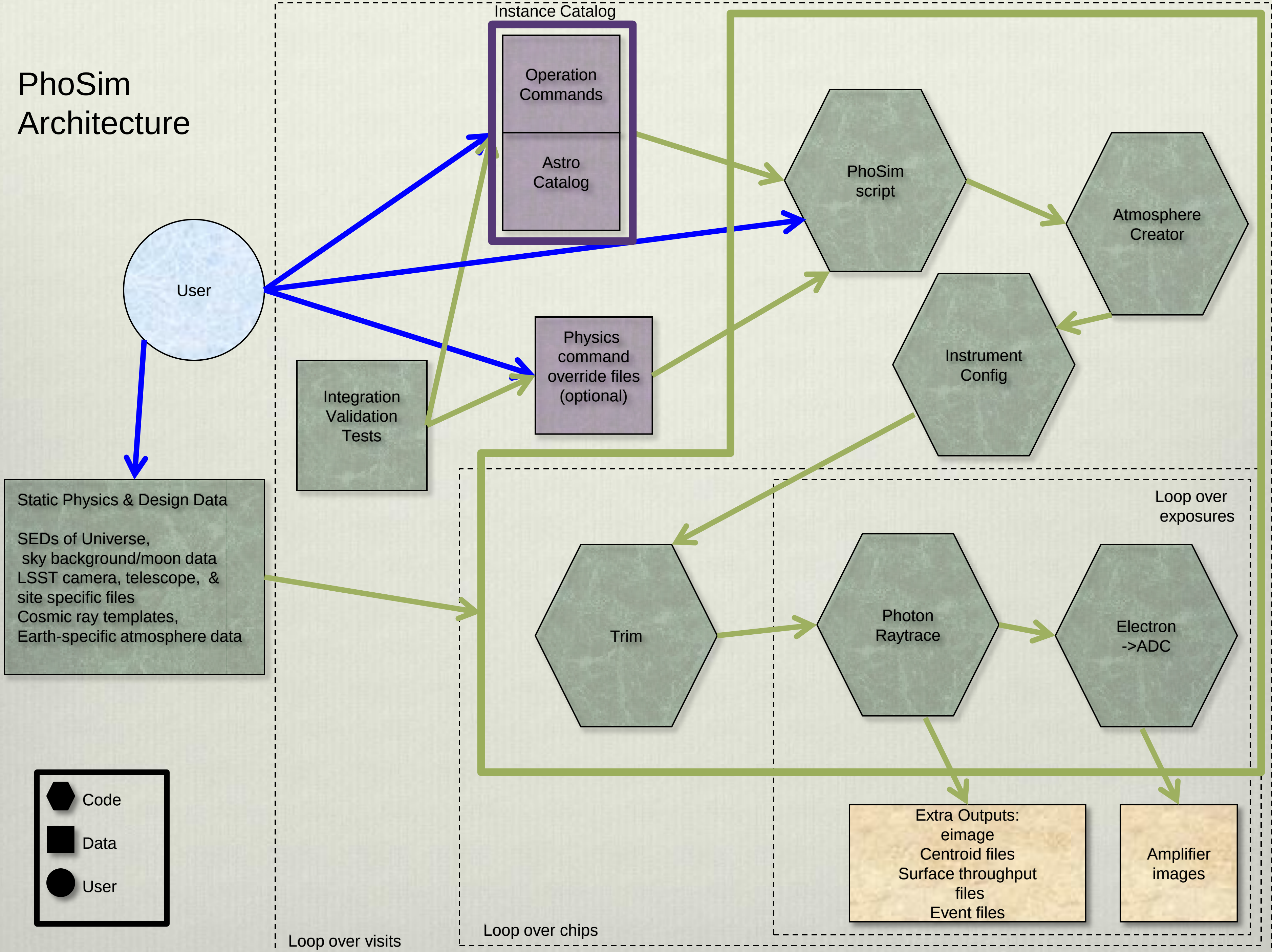




Basically doing a Monte Carlo over the incident radiation field through Time-dependent & Wavelength-dependent Physics

Extremely fast way of doing this integral even if we have large numbers of photons

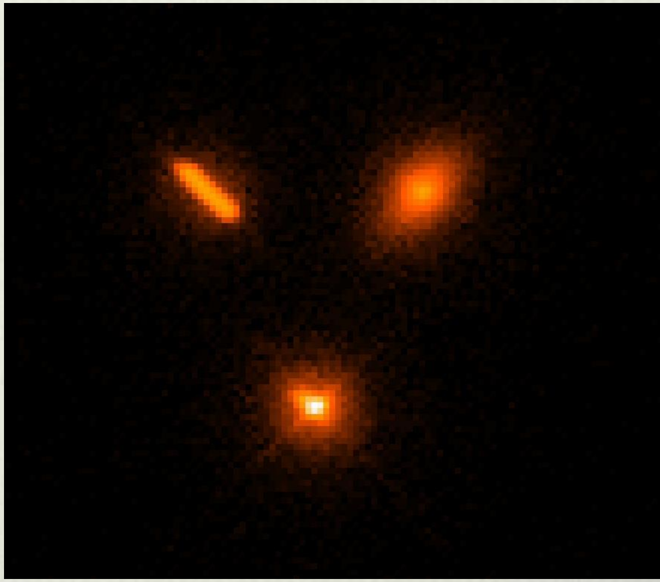
PhoSim Architecture



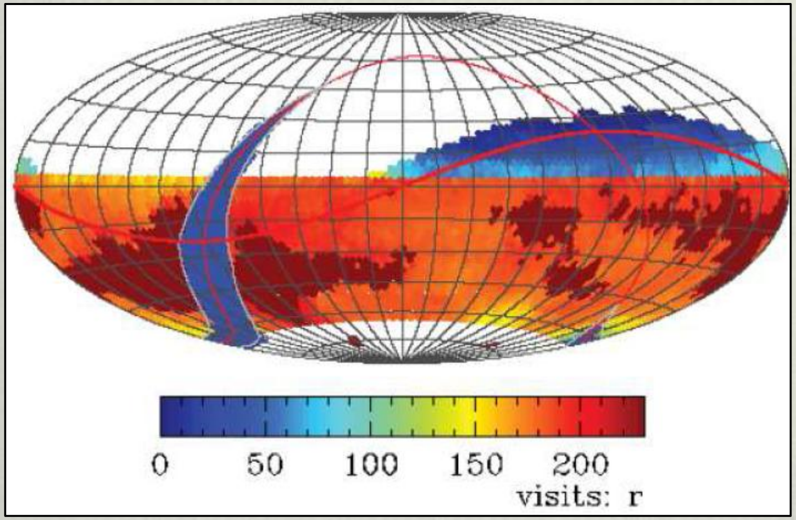
Catalog Constructor

Connolly, Krughoff, Gibson (UW)

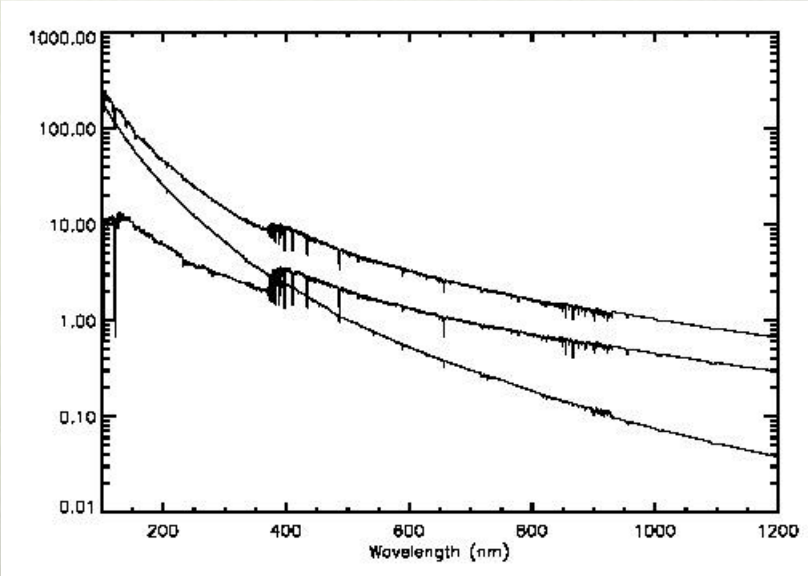
A catalog of positions, motions (proper motions, orbits), and physical properties (types, SEDs, spatial model, etc.) of objects expected to be seen by LSST.
It is a multi-billion row relational database, and a suite of Python tools.



Used to create "instance catalogs" what is in the sky at a given time and what are their spatial & spectral properties;
Include operational data of environment and observation control (moon position, filter, exposure, etc.)



LSST Operation Simulator

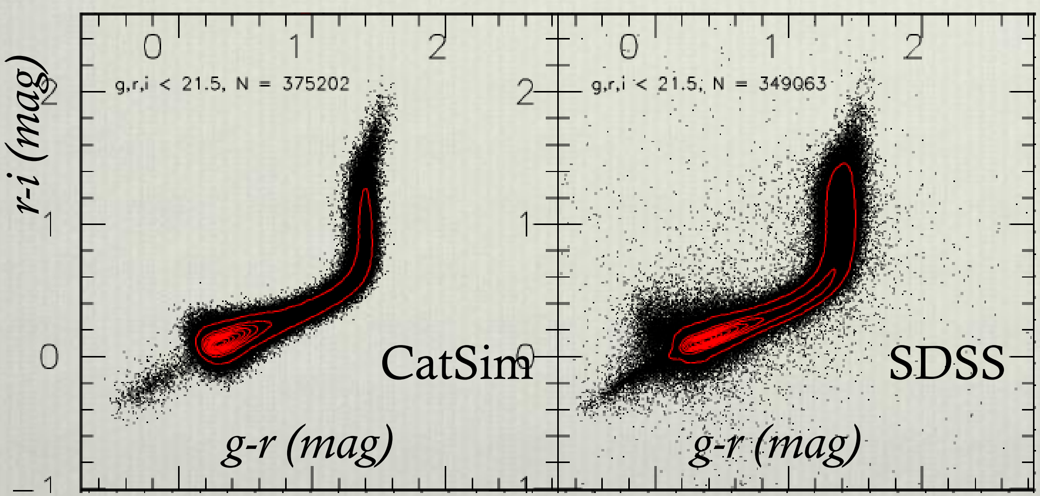


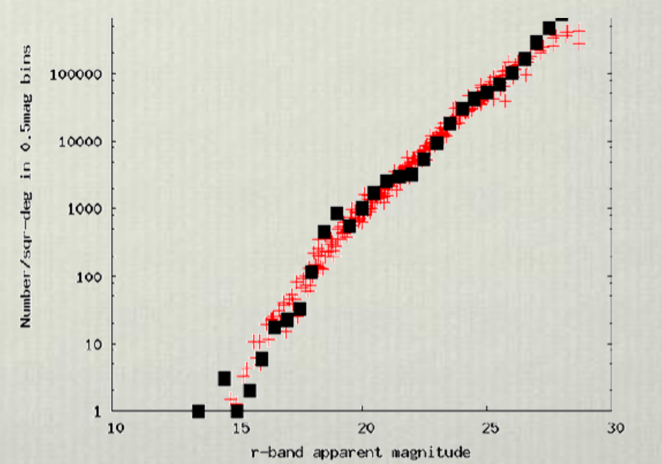
- Galaxies from ΛCDM N-Body Simulations: Galaxy positions and properties from Millennium N-body simulation catalogs with gas cooling, star formation, supernovae and AGN (Lucia et al. 2008); Up to 28 mag in r-band/23 million galaxies
  - Morphologies modeled with combination of Sérsic profiles – ellipticals and bulge + disk (Lucia et al., Gonzalez et al.); Spectral Energy Distribution fit to colors of source using spectral models (Bruzual & Charlot)

- Milky Way model of 10 million detectable stars; Based on state-of-the-art Galactic structure models surveys (Juric et al. (2008), Ivezic et al. (2008), Bond et al. (2010), Sesar, Juric and Ivezic (2011), Lopez-Corredoira et al. (2005)); Includes a full three-dimensional Interstellar dust distribution model to redden SEDs of stars & galaxies (Amores & Lepine (2005), matched to Schlegel, Finkbeiner, Davis (1998) maps at infinity)

- 10.6 M object Solar System Model w/ orbits & obs. Properties: inclues Near Earth Objects,Main Belt Asteroids, Trojans, Trans-Neptunian Objects, Scattered Disk Objects, (PanSTARRS Model, PASP 123, 423 (2011),Bottke et al 2002, Morbidelli et al, Grav et al. 2011)

- Variable stars and transient objects (e.g. SNe)





Draw Photons

- **Direction:** Direction chosen by (ra, dec) and telescope pointing (ra,dec) & rotator angle

- **Wavelength:** Monte Carlo Sample SED files to choose wavelength in rest frame of source

- **Time:** Monte Carlo Sample time between start and stop of exposure

- **Position:** Start at the top of the atmosphere in pupil pattern

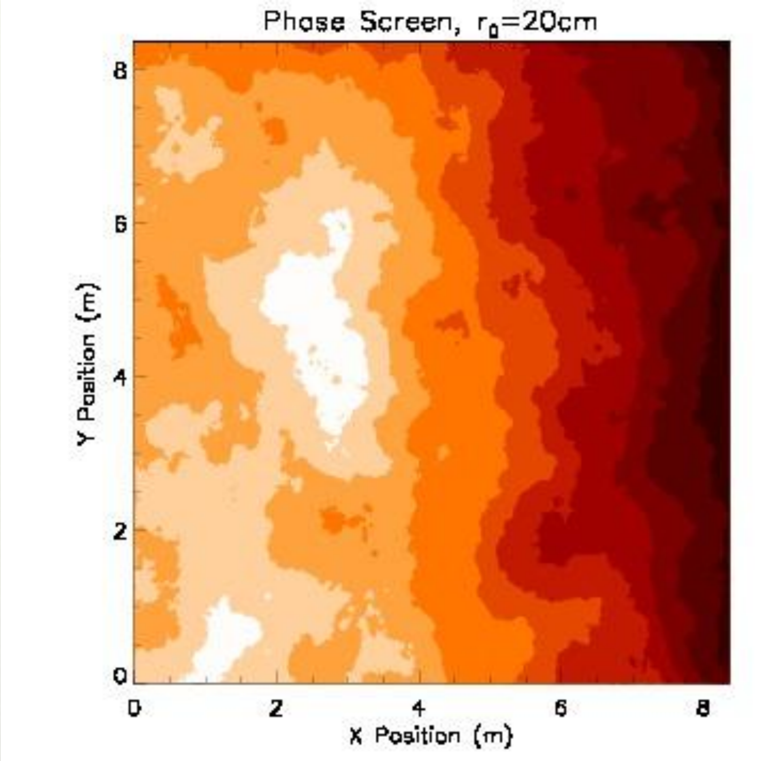
Additional Astrophysics:

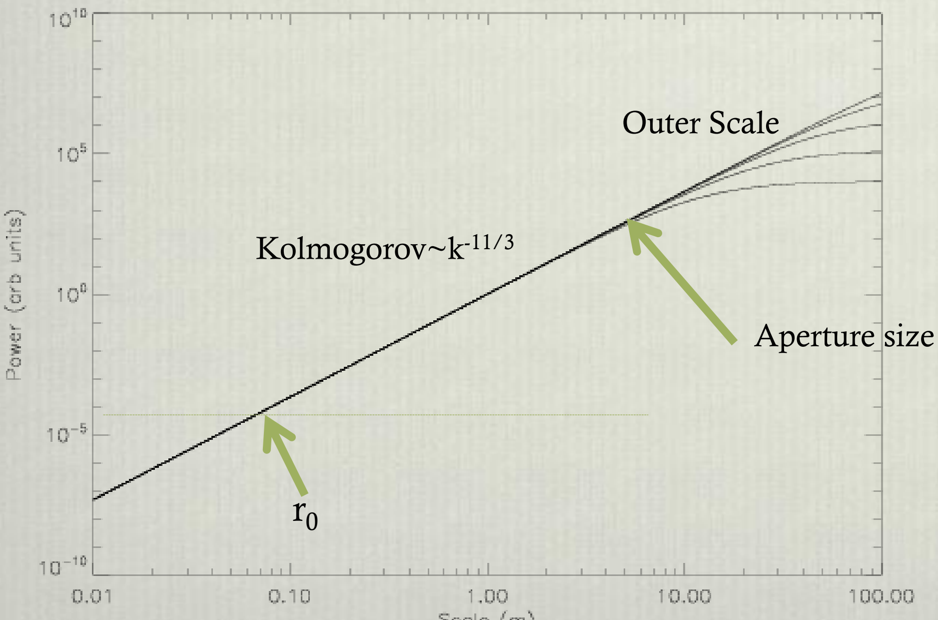
- **Redshift**: photon has wavelength redshifted after drawing from rest frame

- **Dust:** Two dust models that destroy the photons according to reddening laws; Apply both in the rest frame for internal reddening & in our frame from Milky Way models

- **Lensing:** Extended source models can be distorted by measuring their position from the center of the source and distorting final position of photon according to γ_1 and γ_2

Atmosphere Turbulence Phase screens



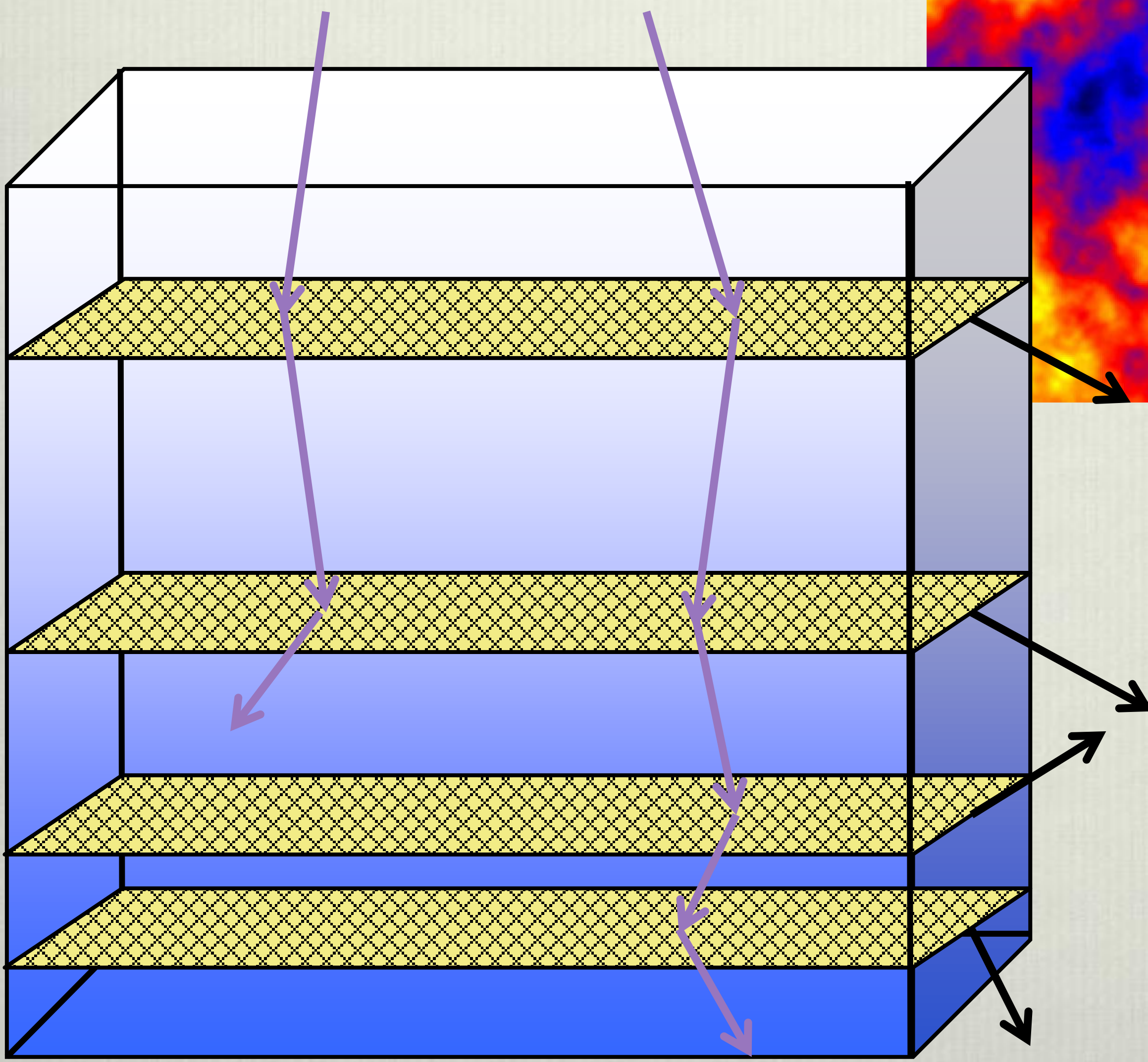


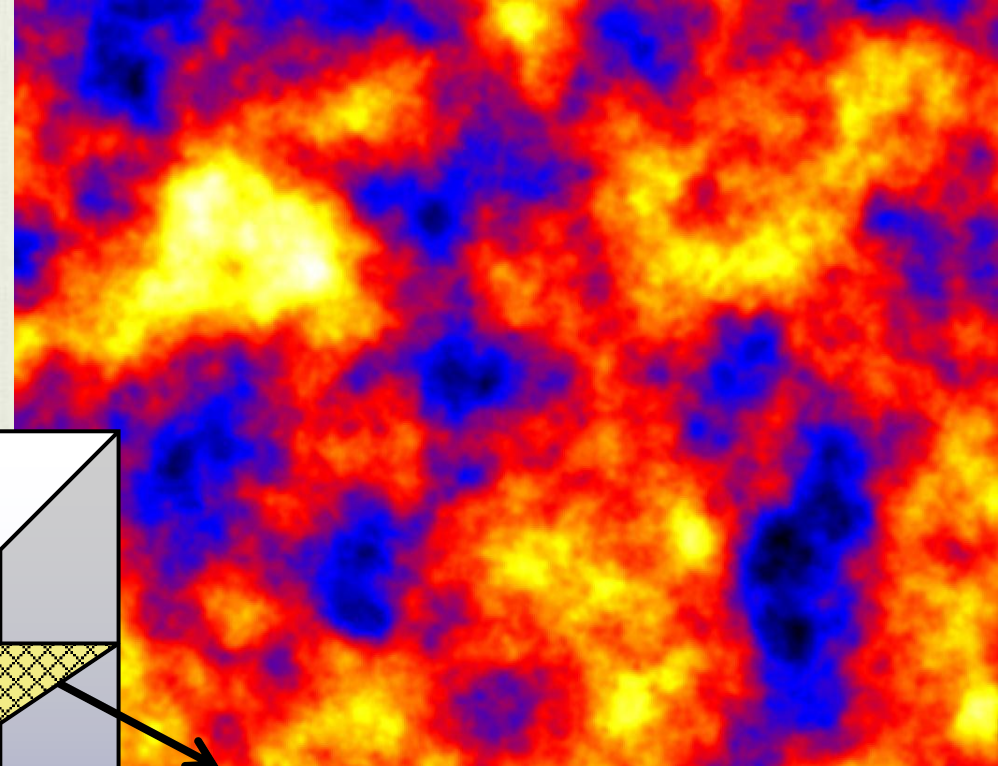
Temperature fluctuation in the atmosphere cause index of refraction variations and result in "seeing"

Well-known that atmospheric turbulence has approximately Kolmogorov spectrum ($k^{-11/3}$) up to outer scale L_0 (von Karman)

These patterns are essentially frozen and drift with constant velocity in a series of layers (Taylor)

Atmosphere Model





Photons accumulate
Refractive kicks through
Frozen drifted phase screens
of turbulence;
Possibly lost due to opacity

Diffraction on scales below 2 r_0
treated by full diffraction calculation

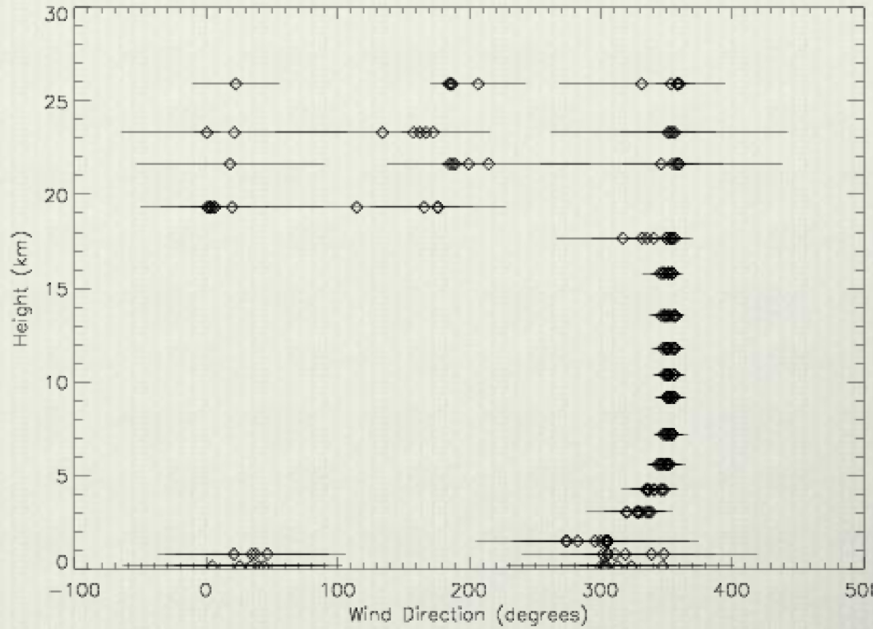
Atmospheric Dispersion simulated

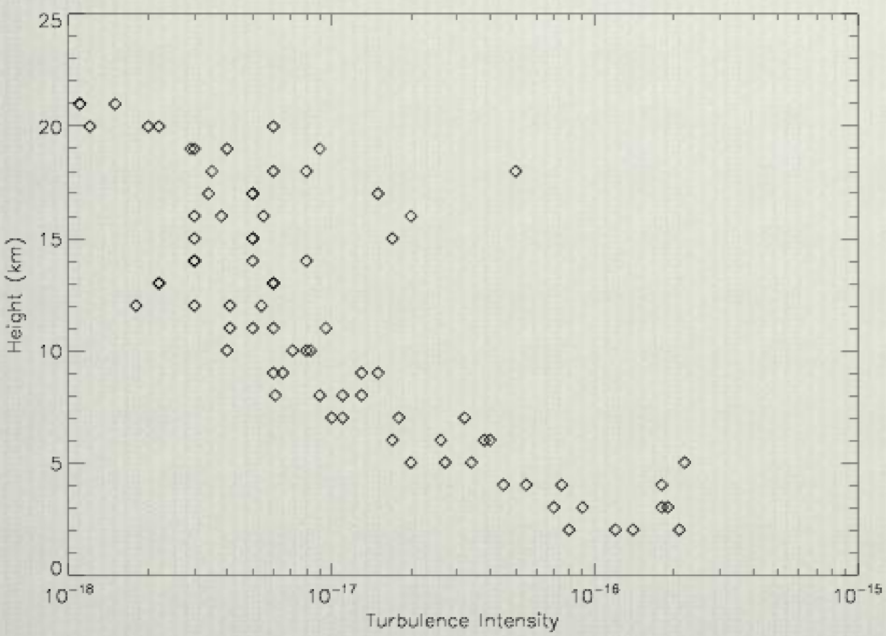
Atmosphere Structure

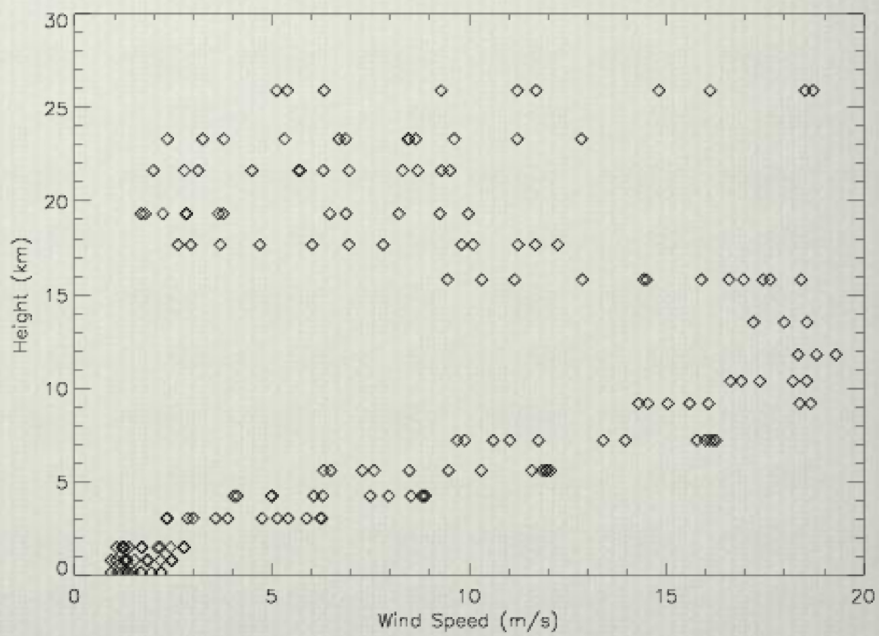
Wind model (direction & data) uses data based on seasonal monthly averages for LSST latitude and longitude

Model for turbulence intensity as a Function of height

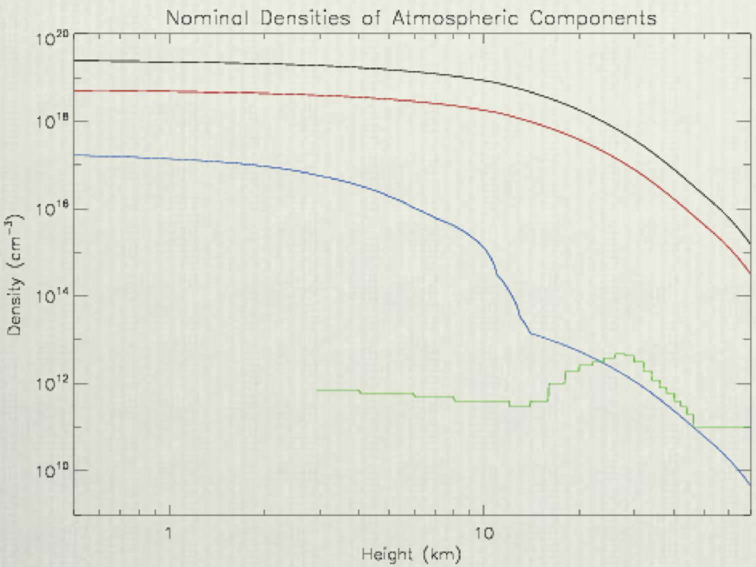
Model for outer scale a function of height

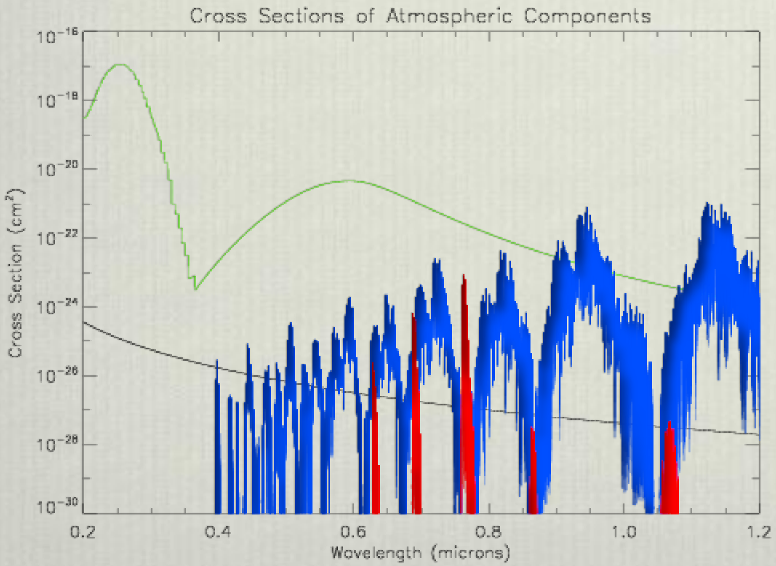






Atmosphere Opacity





1) Cloud model

2) Molecular opacity

- O_3
- O_2
- H_2O

3) Rayleigh scattering

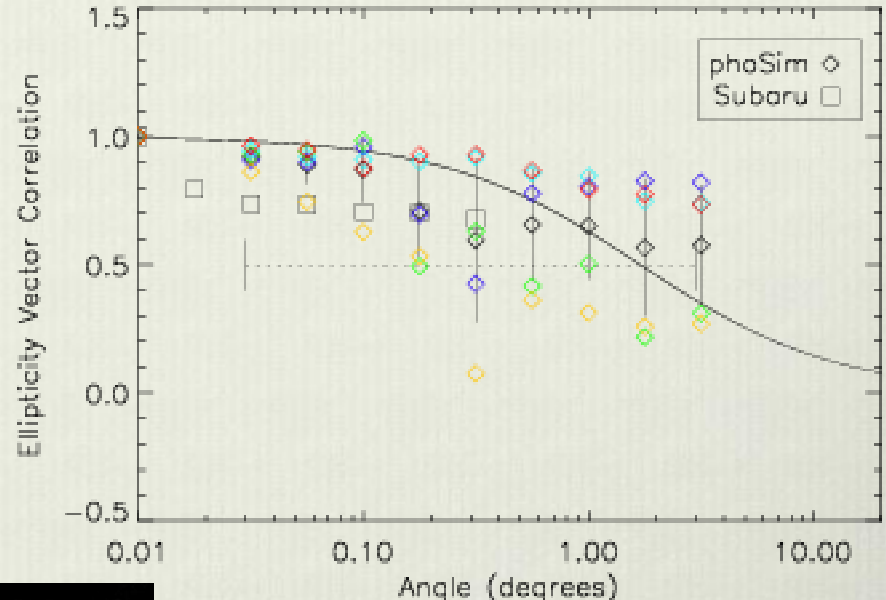
4) Aerosols

Have complex spatial & temporal variation

Local optical depth calculated for each ray segment

Absorption is pressure-dependent and therefore height dependent

Star Grids



phaSim ◇
Subaru □
Ellipticity Vector Correlation
Angle (degrees)
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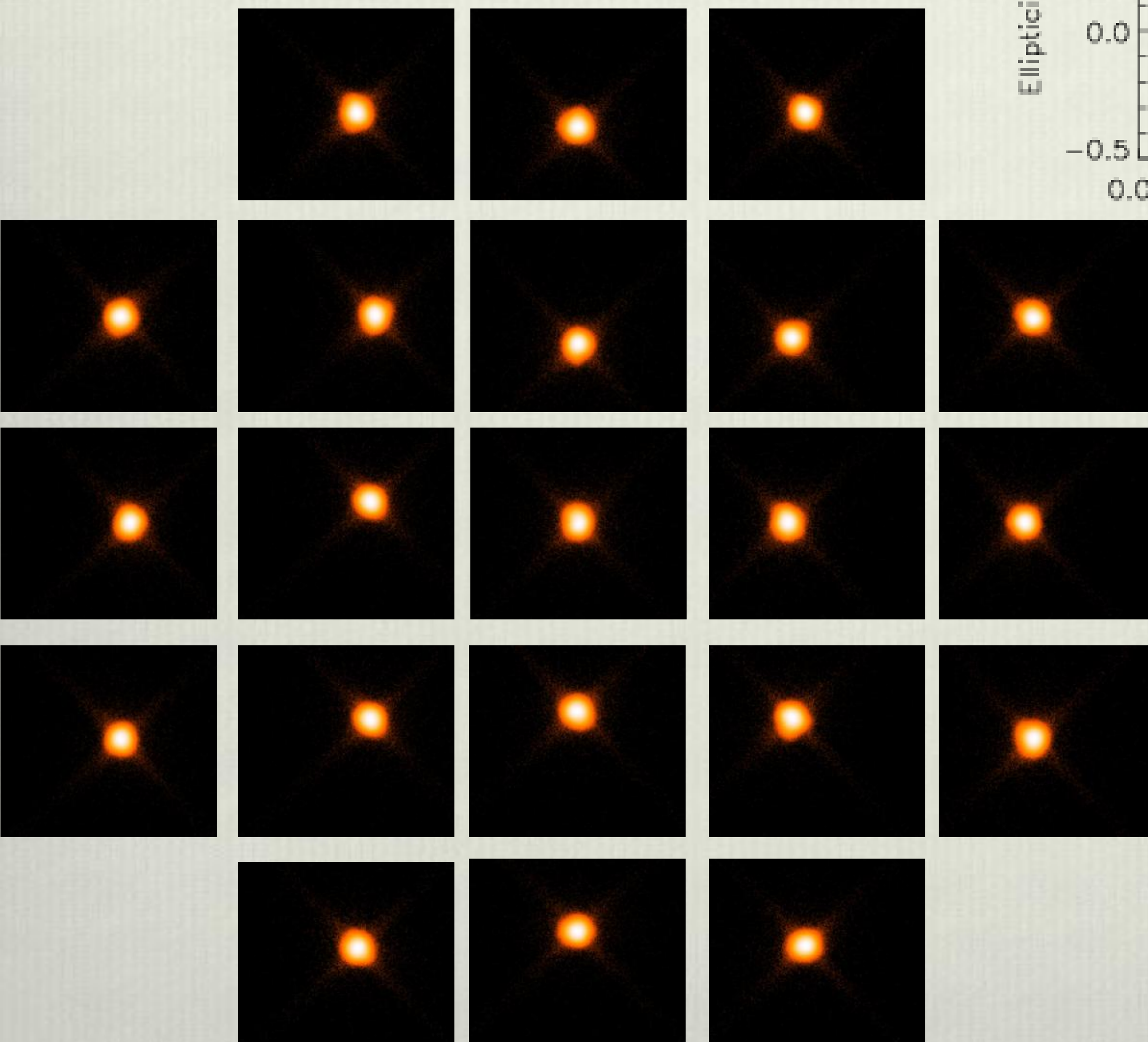
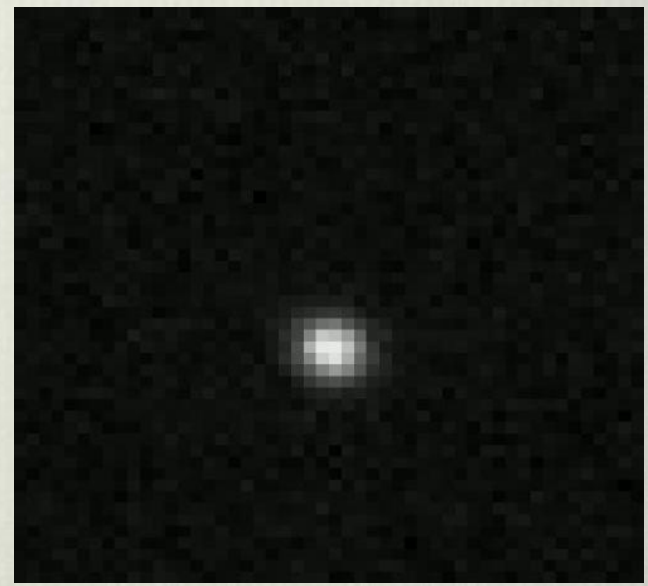
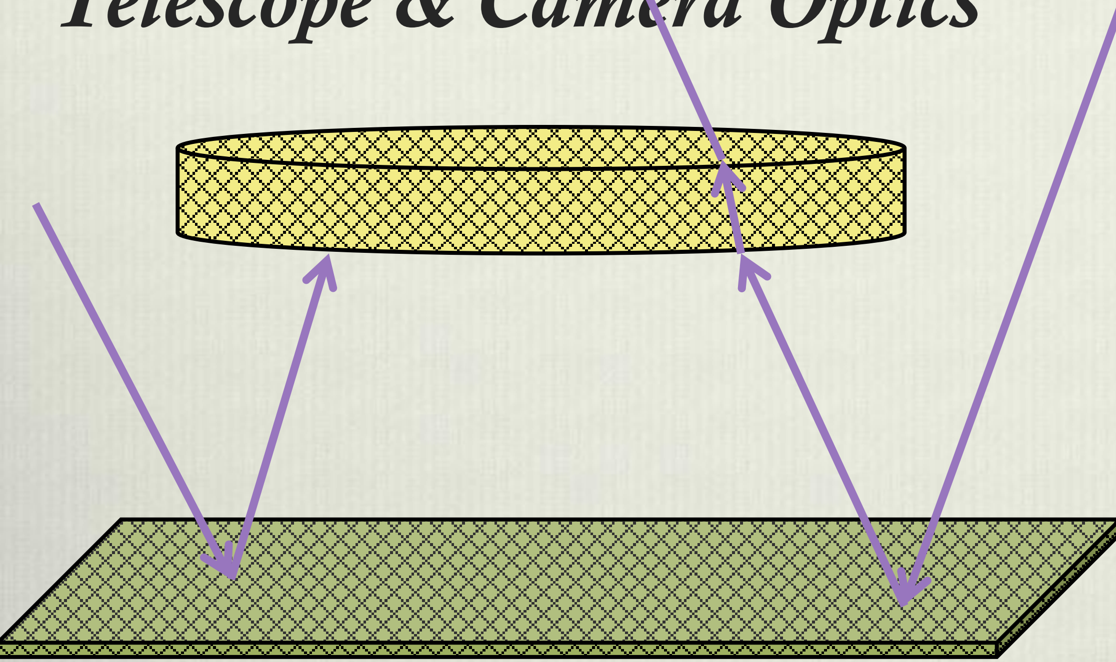
1.00
10.00





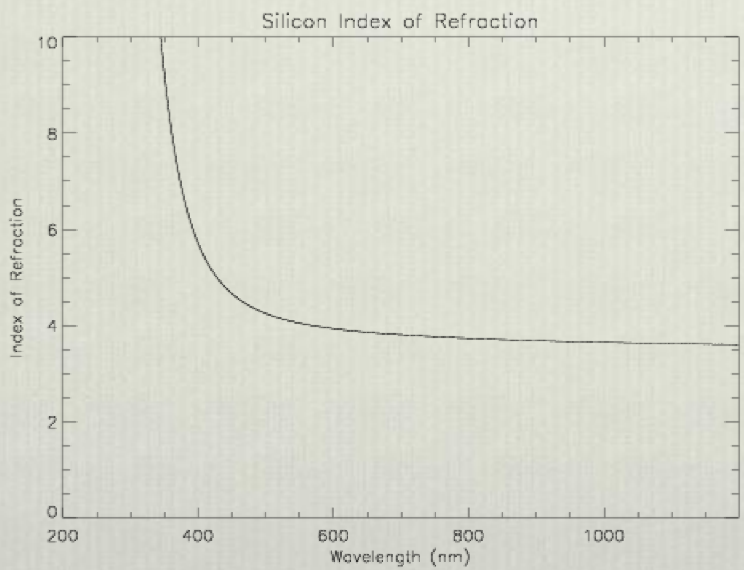
Raytracing through Telescope & Camera Optics

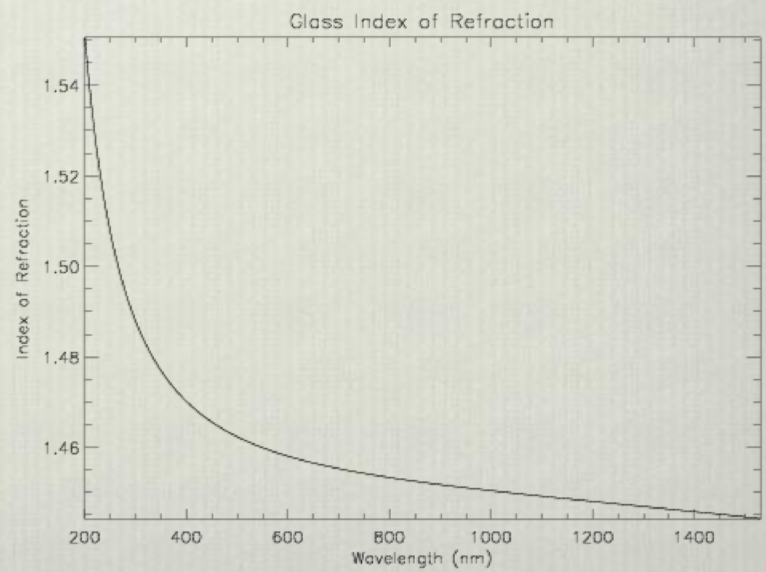


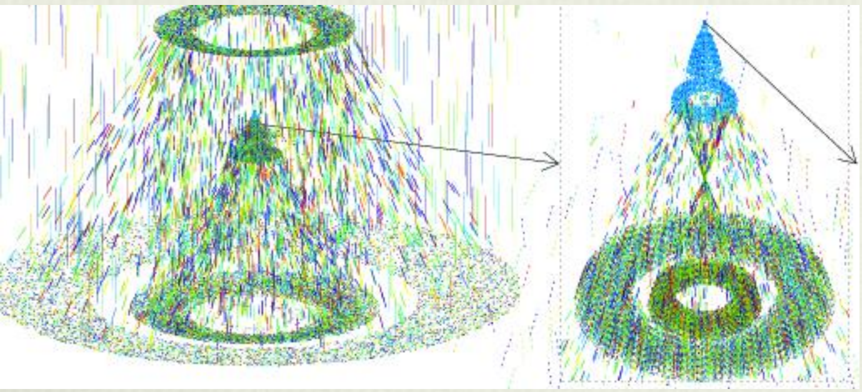
Series of optical surfaces (2D) that divide the 3-D volume into different media (glass, silicon, air)

Ray intercepts are found by minimizing the distance between the end of the ray and the surface

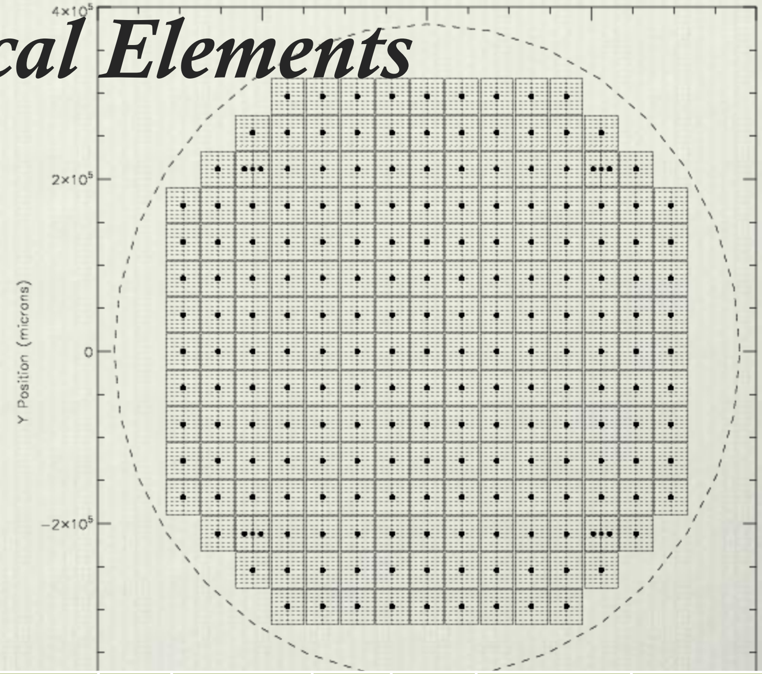
Interactions can occur at interfaces (reflection, refraction, absorption)





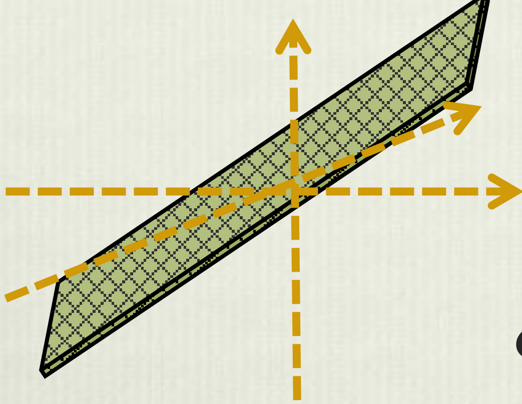


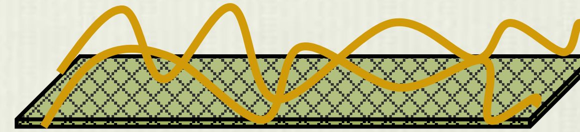
Optical Elements



Each filter configuration has every surface defined by the asphere equation
Each surface specifies the media (silicon, glass, air) between the surface in the 3-D volume
Chips in detector plane specified by rectangular surfaces having a nominal center, pixel size, x & y sizes

Name	Type	R_{curv}	Δz	r_{out}	r_{in}	κ	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	Coating	Medium
M1	Mirror	19835	0	4180	2558	-1.215	0	0	0	1.381e-27	0	0	0	0	Mirror	Vacuum
M2	Mirror	6788	6156.2	1710	900	-0.222	0	0	0	-1.274e-23	0	-9.68e-31	0	0	Mirror	Vacuum
M3	Mirror	8344.5	-6390	2508	550	0.155	0	0	0	-4.5e-25	0	-8.15e-33	0	0	Mirror	Vacuum
None	None	0	3630.5	0	0	0	0	0	0	0	0	0	0	0	None	Vacuum
L1	Lens	2824	34.568418	775	0	0	0	0	0	0	0	0	0	0	Lens A/R	Glass
L1E	Lens	5021	82.23	775	0	0	0	0	0	0	0	0	0	0	Lens A/R	Vacuum
L2	Lens	0	412.64202	551	0	0	0		0	0	0	0	0	0	Lens A/R	Glass
L2E	lens	2529	30	551	0	-1.57	0		0	1.656e-21	0	0	0	0	Lens A/R	Vacuum
F	filter	5632	349.58	378	0	0	0		0	0	0	0	0	0	Filter 0	Glass
FE	filter	5530	26.60	378	0	0	0		0	0	0	0	0	0	None	Vacuum
L3	lens	3169	42.40	361	0	-0.962	0		0	0	0	0	0	0	Lens A/R	Glass
L3E	lens	-13360	60	361	0	0	0		0	0	0	0	0	0	Lens A/R	Vacuum





Perturbations, Misalignments, & Tracking Errors

Every optical surface & CCD has an ideal location

During a particular simulation all surfaces & CCDs can be misaligned by the 6 degrees of freedom; Each optical surface can also have a surface perturbations place on the surface that represent the deviation from the ideal shape

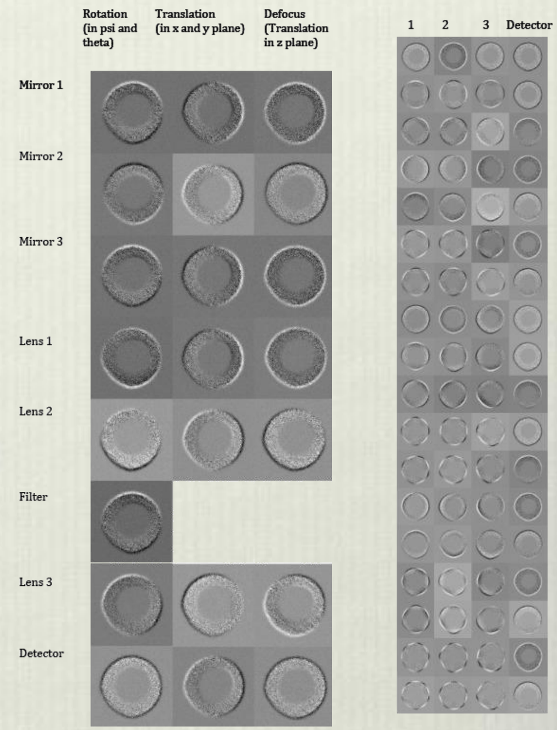
These represent the perturbations & misalignments induced by the thermal, vibrational, pressure, gravitational stresses while the telescope is operating with the full control system as well as fabrication errors

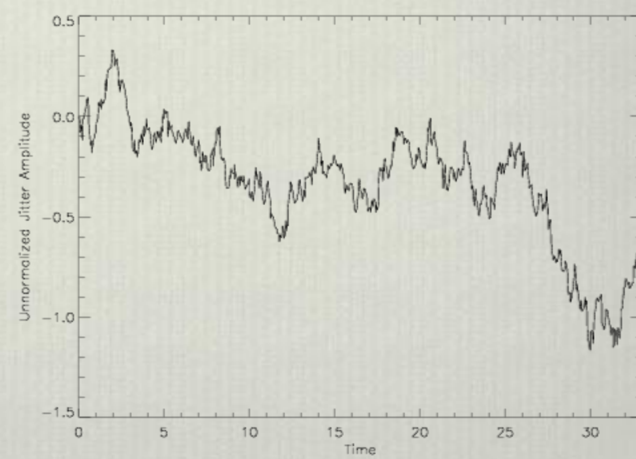
In general, the perturbations & misalignments tend to induce anisotropic PSFs that are highly correlated across the entire focal plane (because mostly in pupil plane)

Also have tracking model for perturbations during an exposure

$$\delta x_i = f_i u_\infty + \frac{dx_i}{dT}\left(T - T_0 + \delta T g_T\right) + \frac{dx_i}{d\theta}\left(\theta + \delta\theta g_m\right) + h_i g_0 + A_{ij}\left(a_j + \delta a_j g_a\right)$$

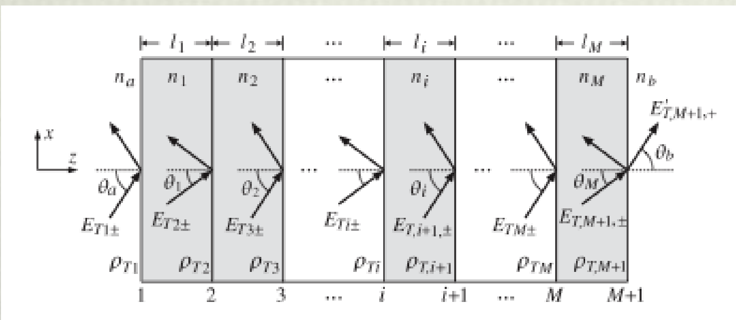
$$a_j = A^{-1}_{ji} P_i + A^{-1}_{jl} Z^{-1}_{lk} \left(1 + \frac{a_k}{\sqrt{N_{avg}}} g_0\right) Z_{ki} U_i$$

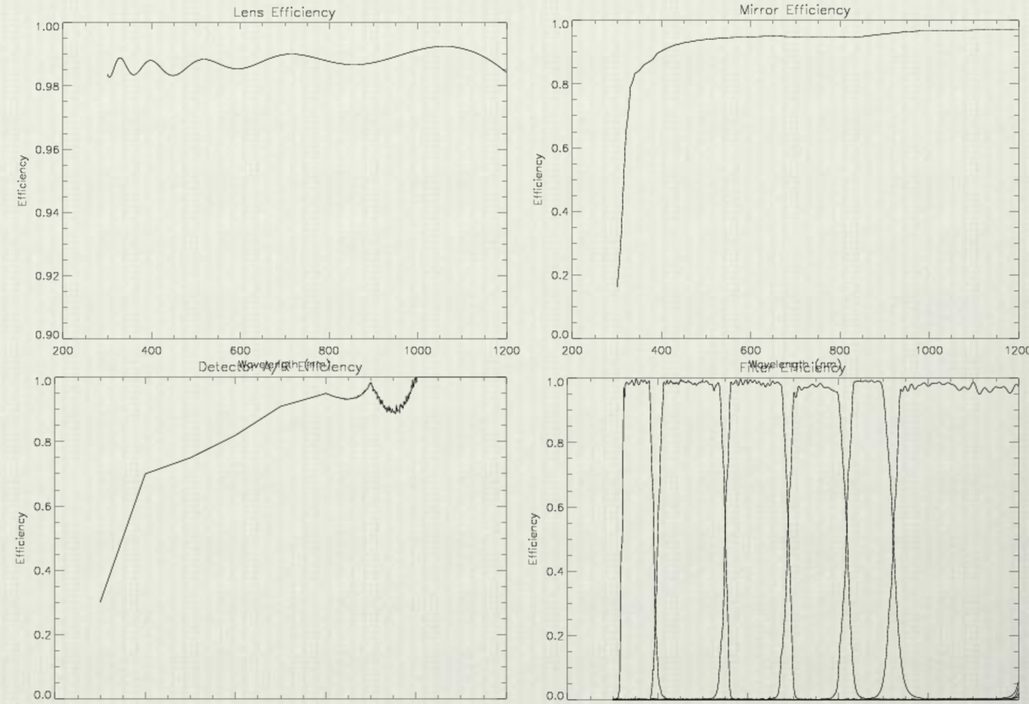




Multilayer Coatings

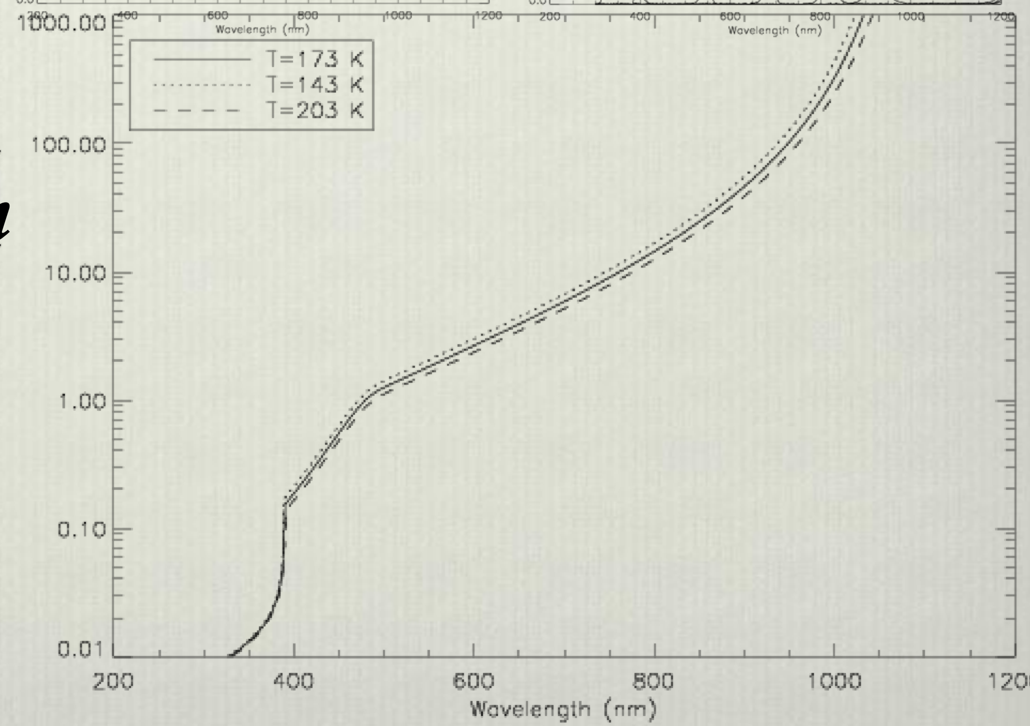
Photons reflected or transmitted according to multilayer models which are angle and wavelength dependent





Photoelectron Conversion

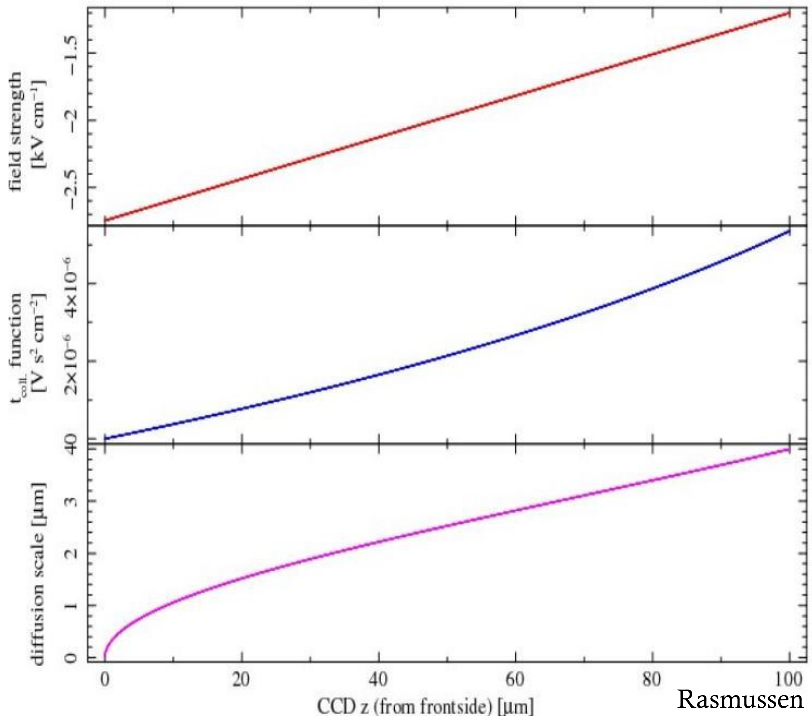
Photons can convert into electrons as they traverse the Silicon (temperature-dependent)



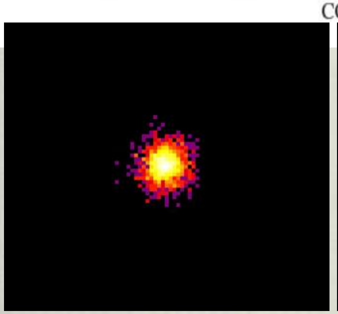
Electron Diffusion

First, electric field profile as a function of height is calculated (voltage & dopant density model dependent)

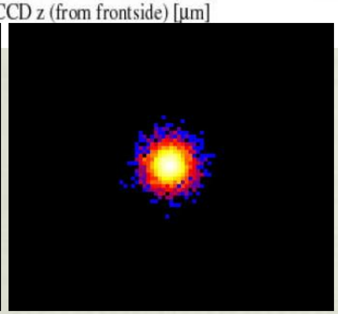
Then electron is drifted in segments and lateral diffusion is set by local diffusion constant; Leads to non-gaussian profile



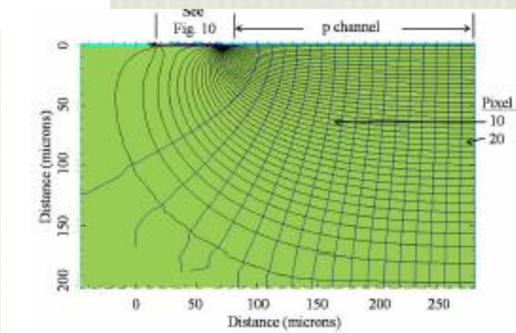
Rasmussen

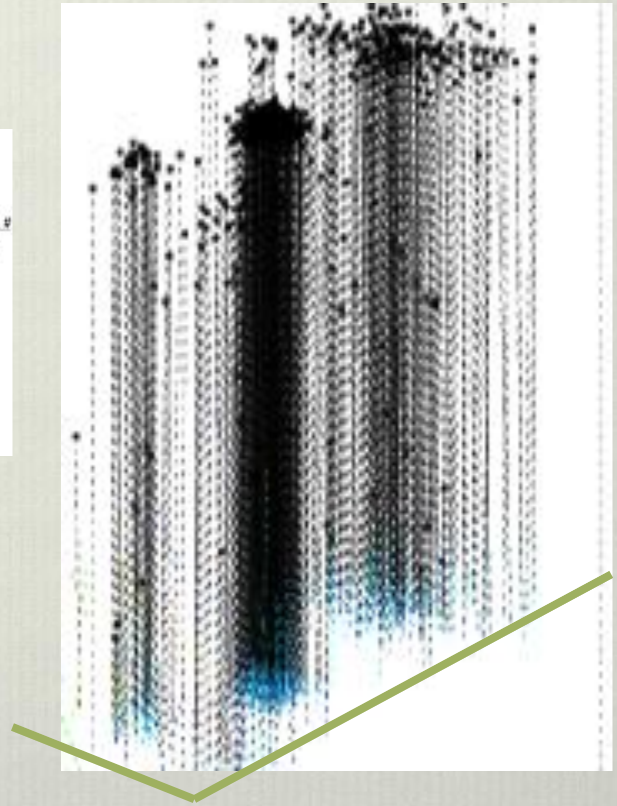


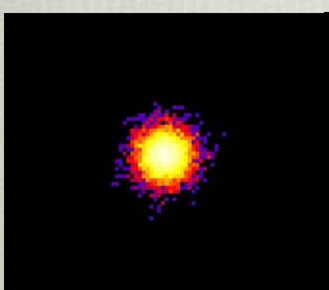
After 1 micron



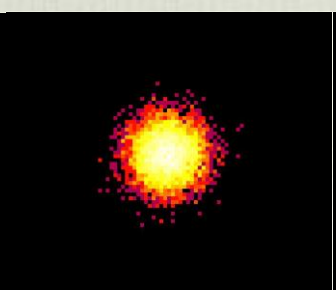
After 10 microns



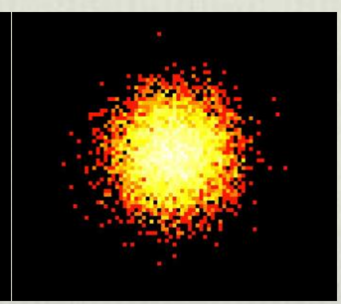




After 50 microns



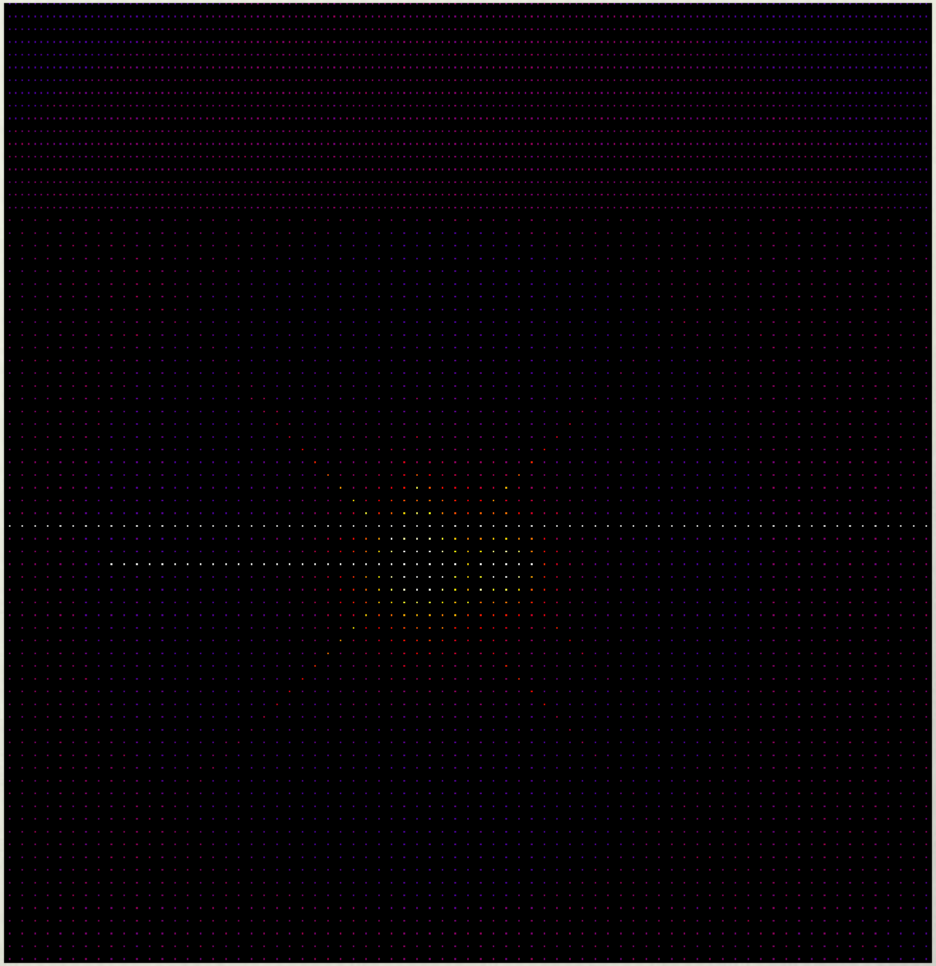
After 100 microns

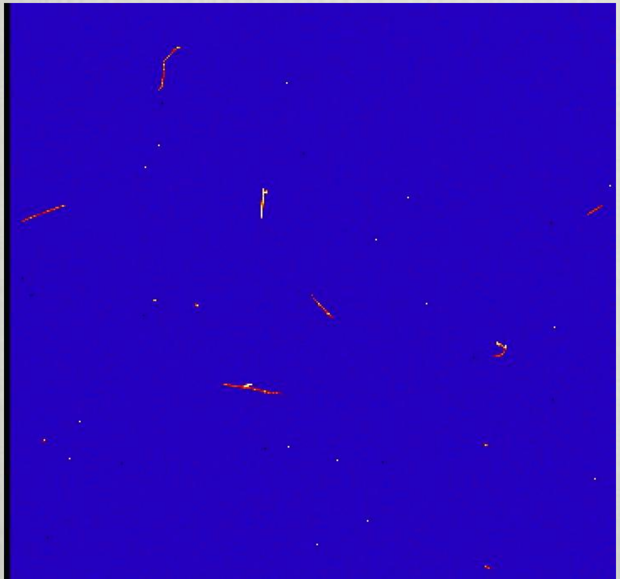


After 300 microns

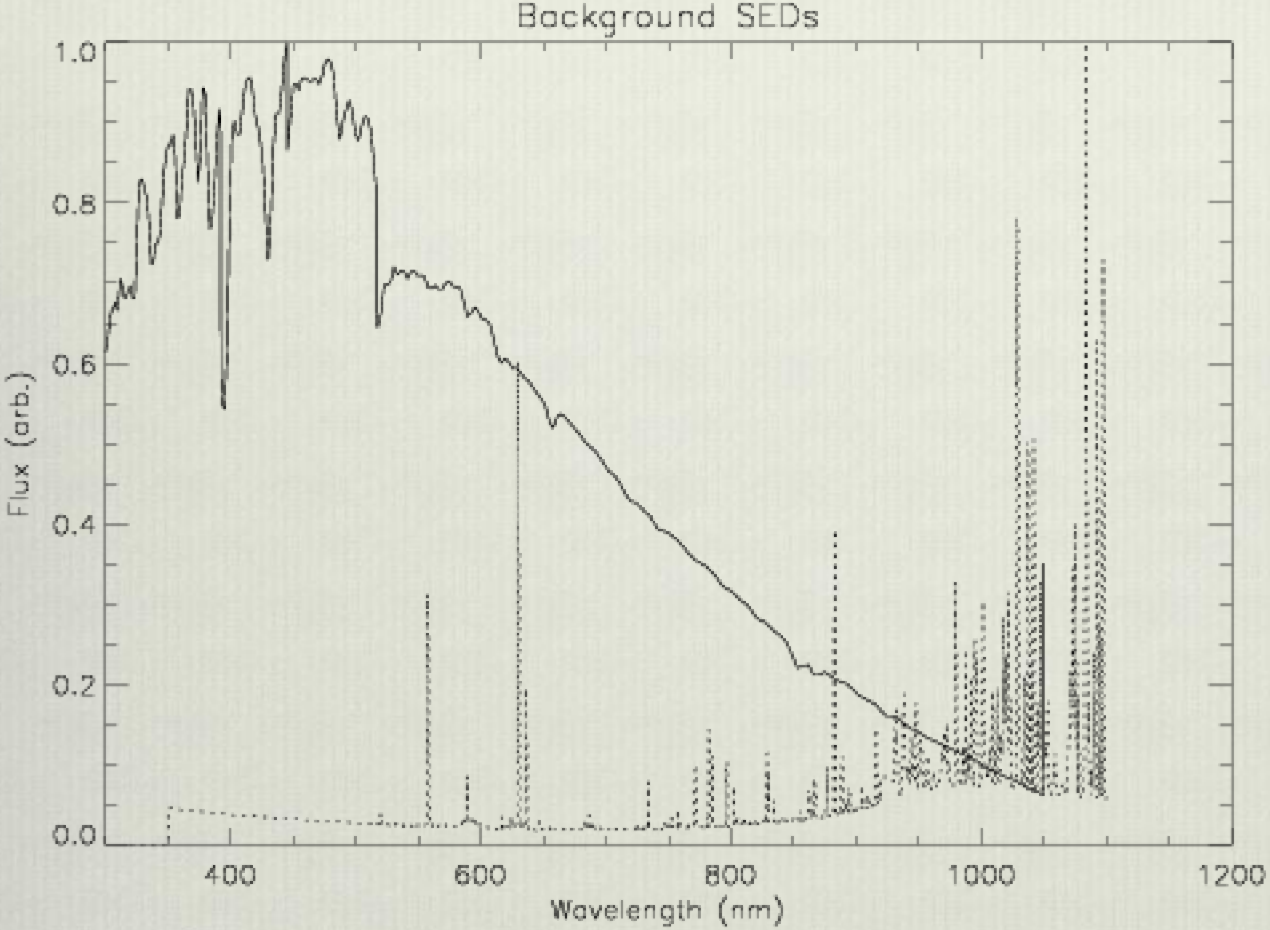
Other Effects

- Spider diffraction
- Dome seeing
- Large angle scattering from mirror micro-roughness & Mie scattering
- Bleeding & Saturation
- Ghosts
- Cosmic Rays





Background Model

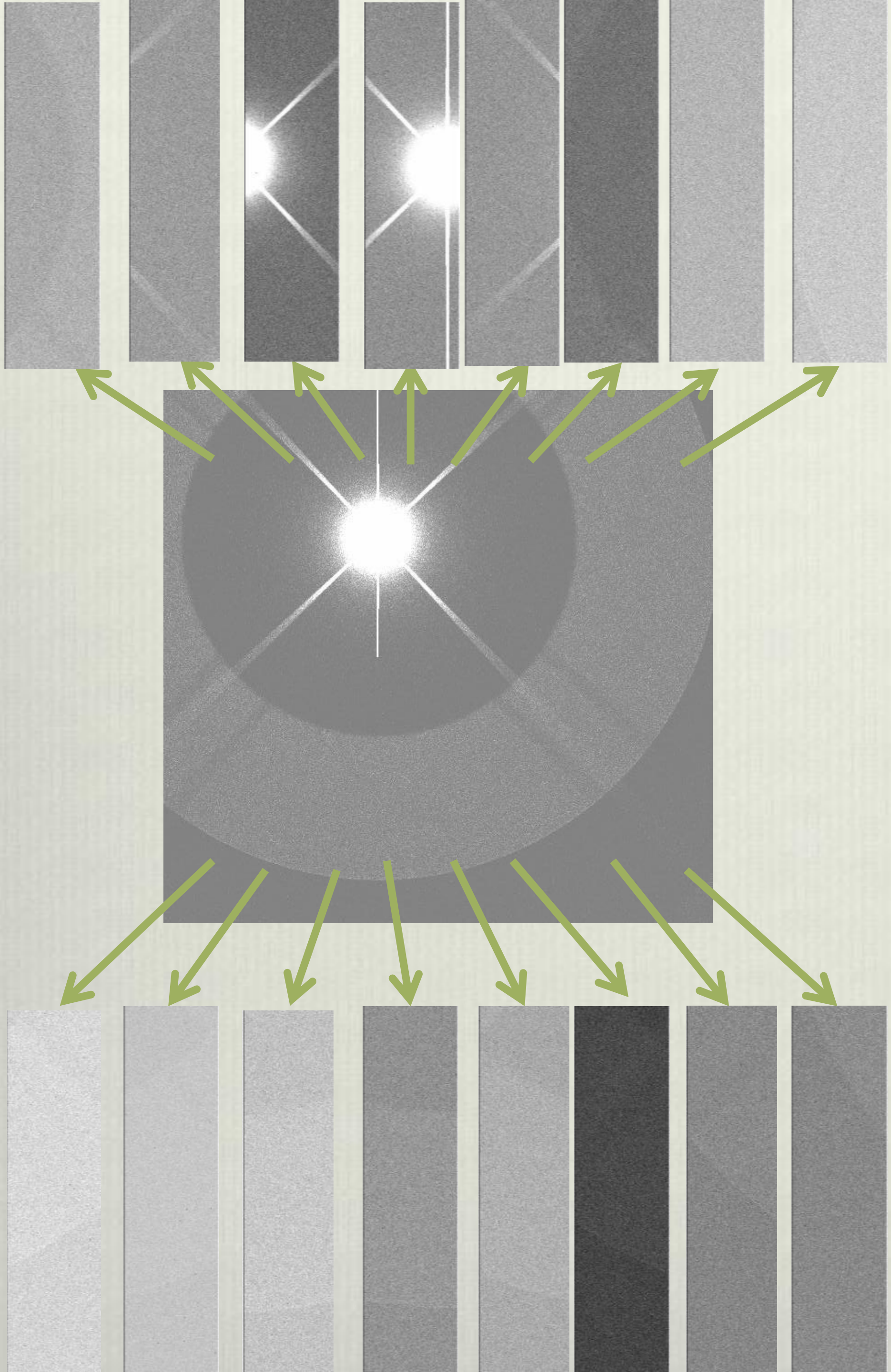


Two components:
Air glow & scattered Moonlight

Moon has Mie scattering & Rayleigh scattering which leads to color-dependent spatial gradient

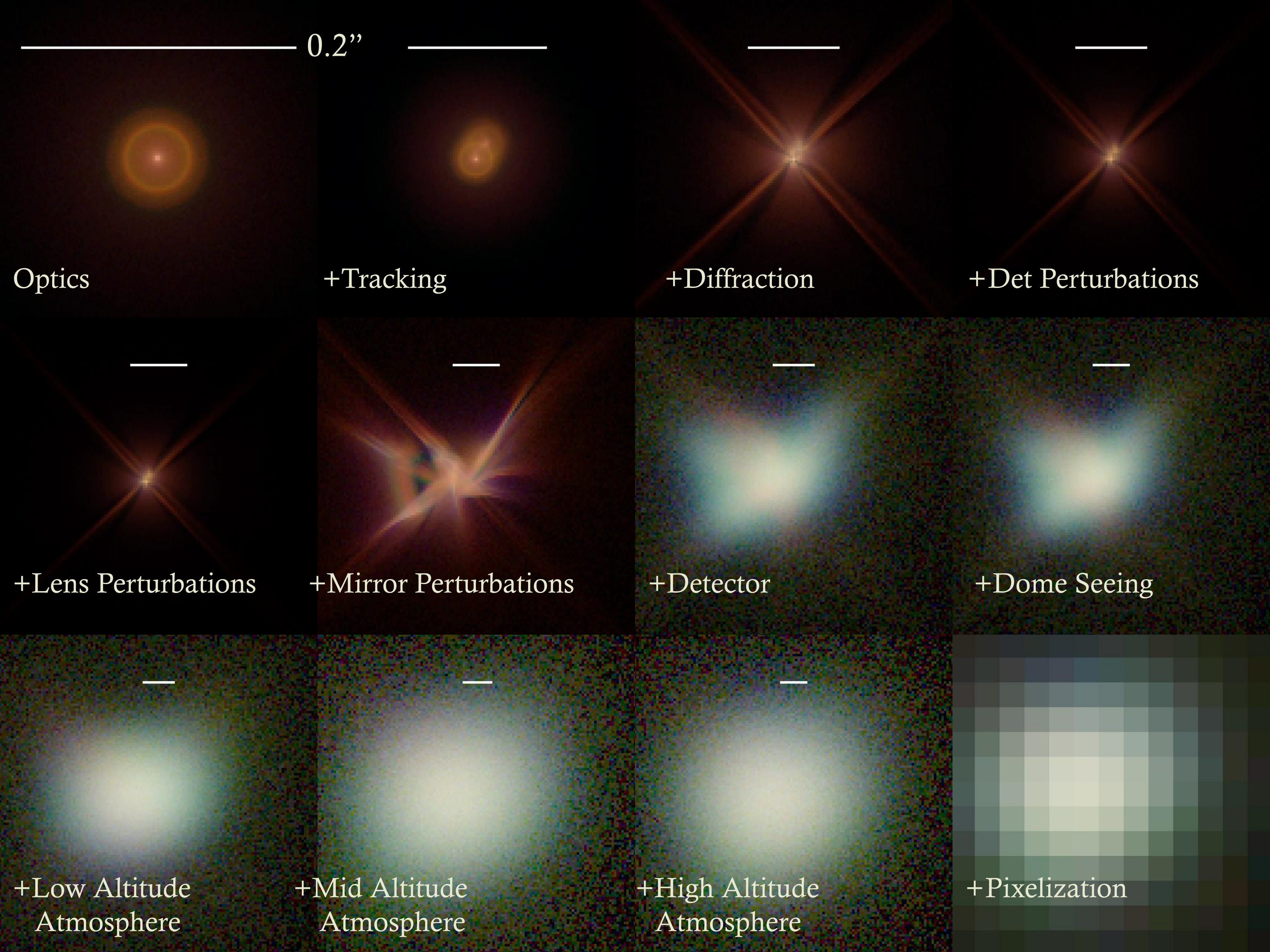
Airglow has spatial variation & temporal variation

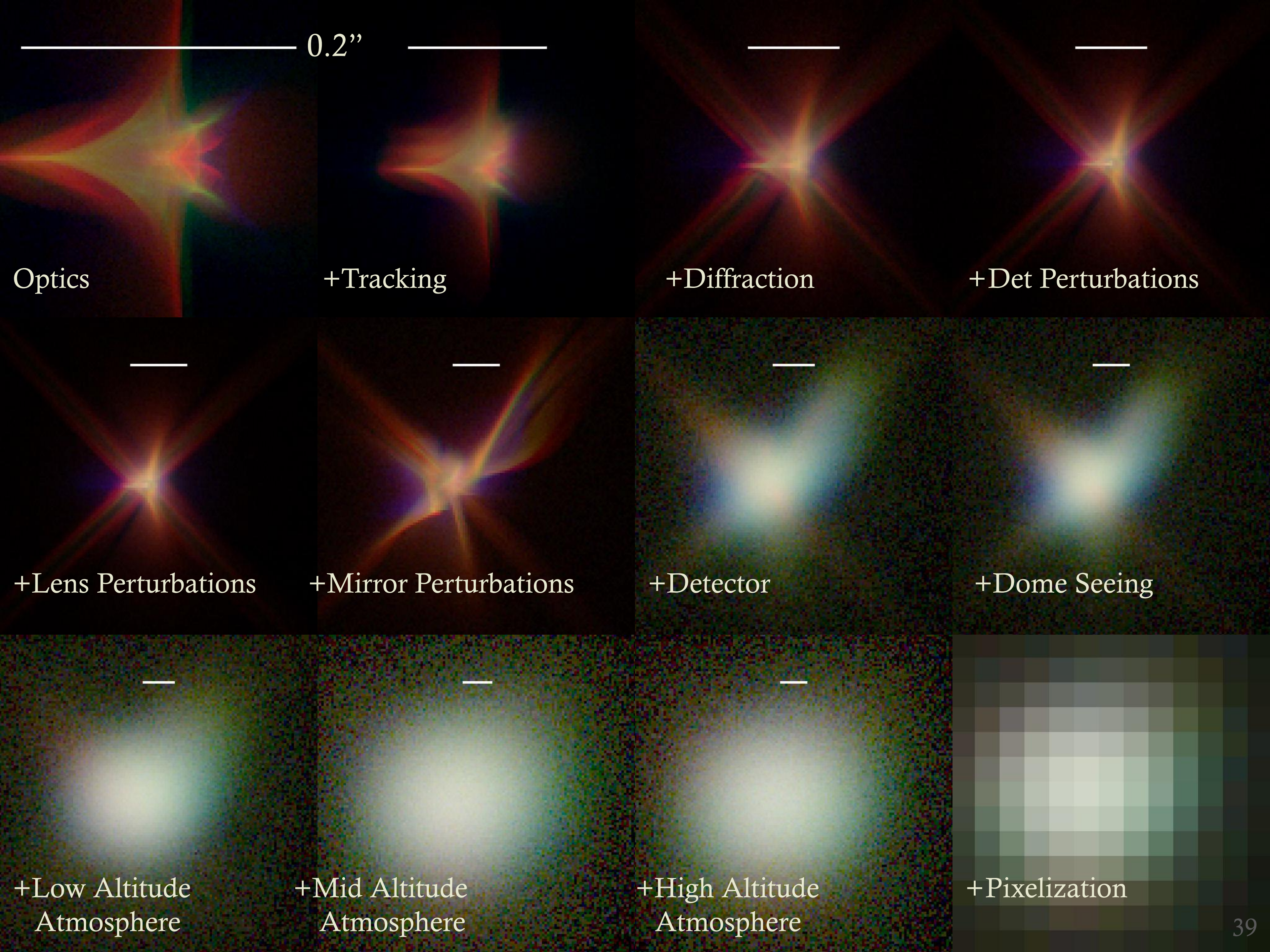
Adams et al.



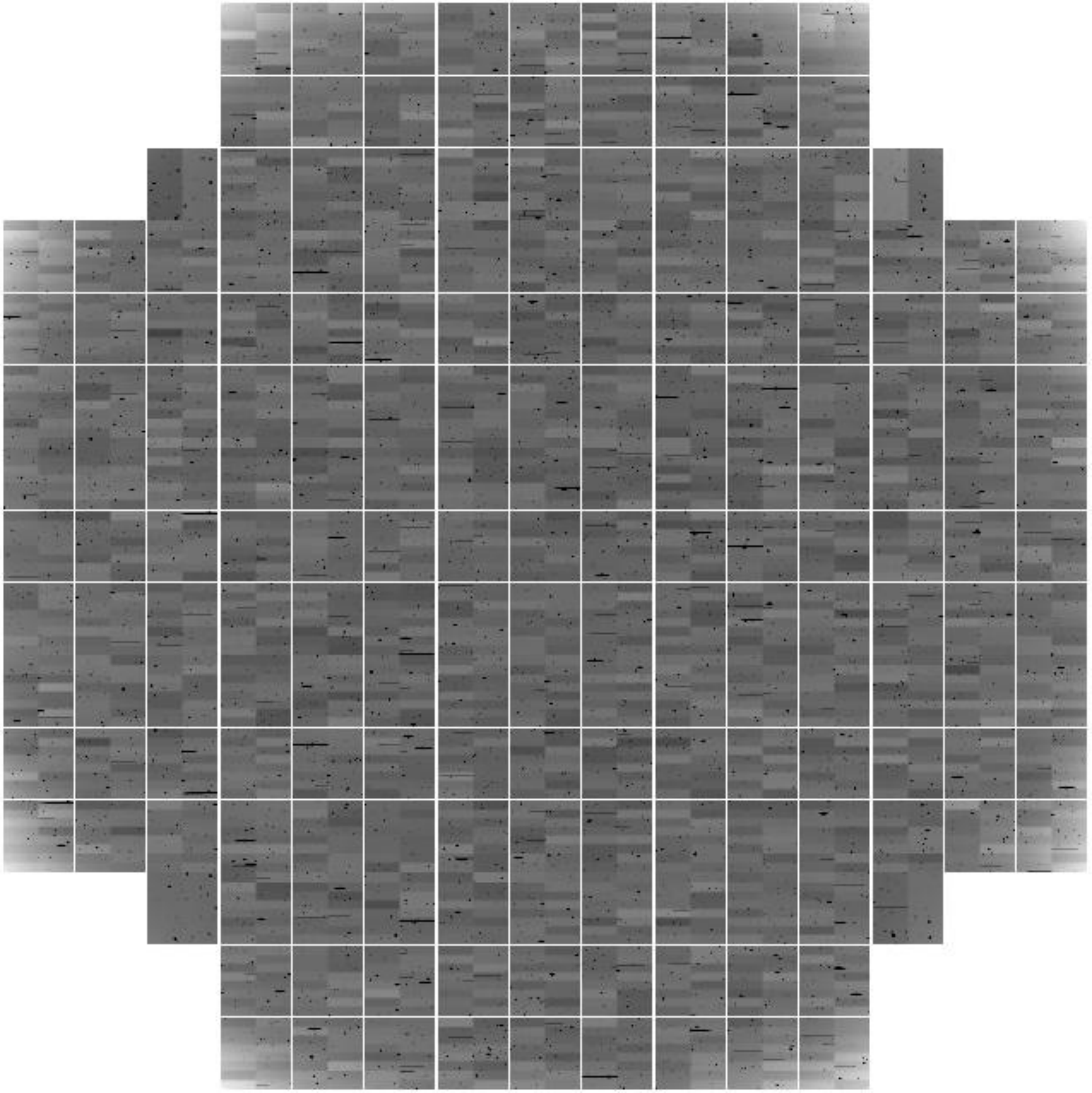
Digitization

- Amplifier Segmentation
- CTE (one electron at a time)
- Pre/Over scans
- ADC using bias, gain, non-linearity model with variation
- Bit error in ADC
- Dark current
- Read noise & variation
- Hot pixels
- Hot columns
- Dead Pixels
- PRNU


0.2”
Optics
+Tracking
+Diffraction
+Det Perturbations
+Lens Perturbations
+Mirror Perturbations
+Detector
+Dome Seeing
+Low Altitude Atmosphere
+Mid Altitude Atmosphere
+High Altitude Atmosphere
+Pixelization

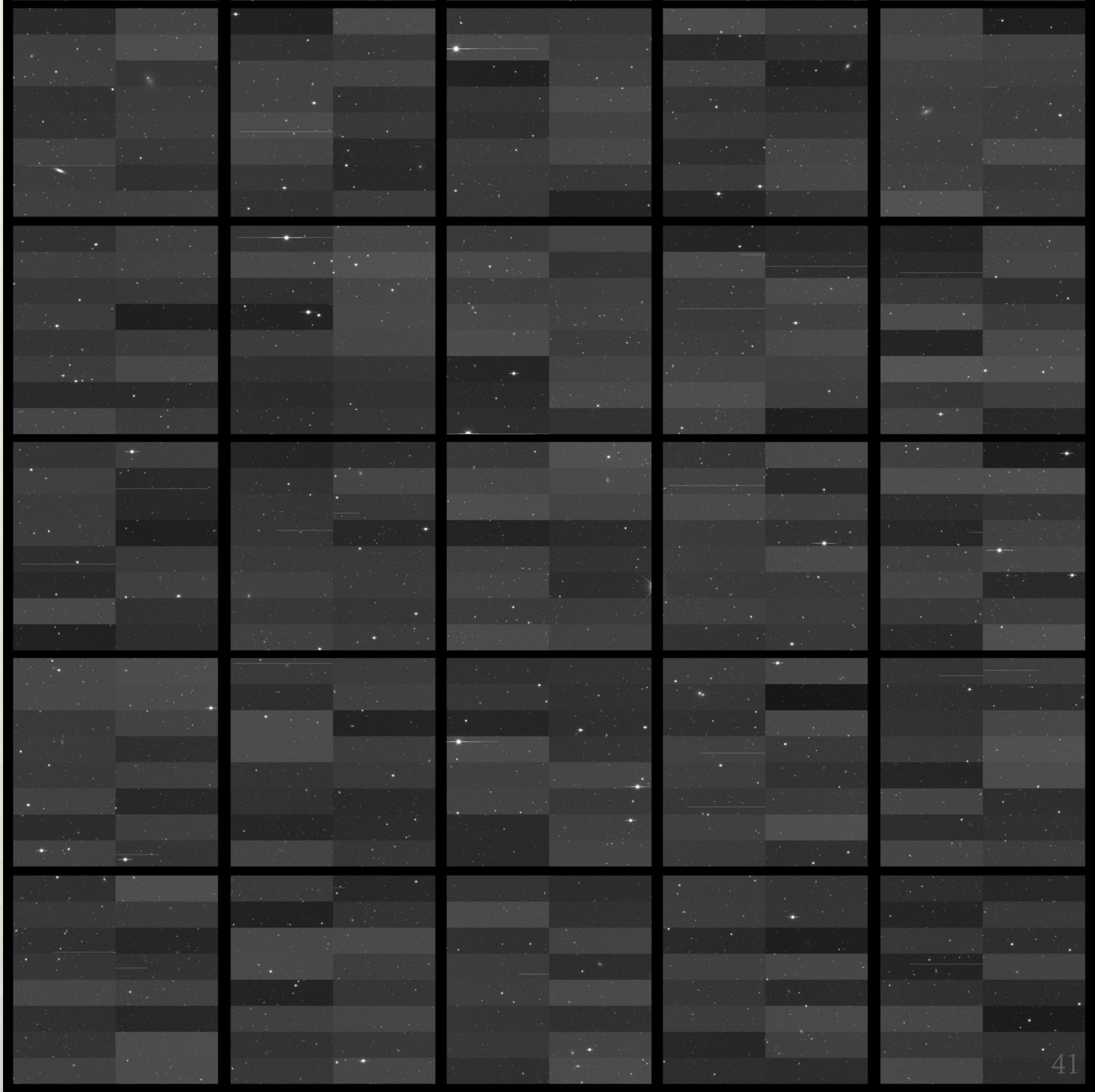

0.2”
Optics
+Tracking
+Diffraction
+Det Perturbations
+Lens Perturbations
+Mirror Perturbations
+Detector
+Dome Seeing
+Low Altitude Atmosphere
+Mid Altitude Atmosphere
+High Altitude Atmosphere
+Pixelization

- Entire focal plane
- 3 gigapixels
- 1000 CPU hours
- 1 trillion photons
- Done on grid computing



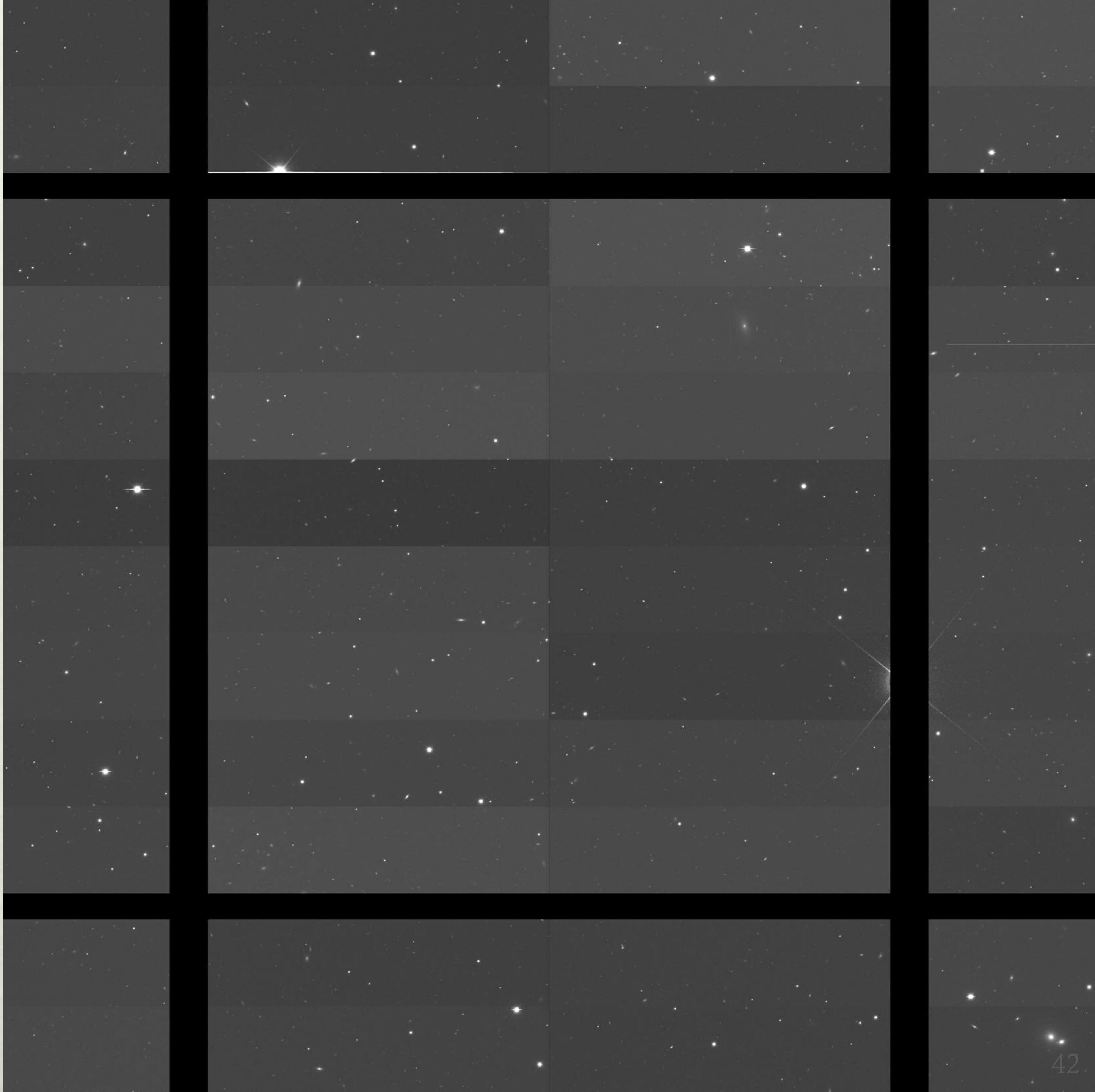
Central
5 x 5 chips

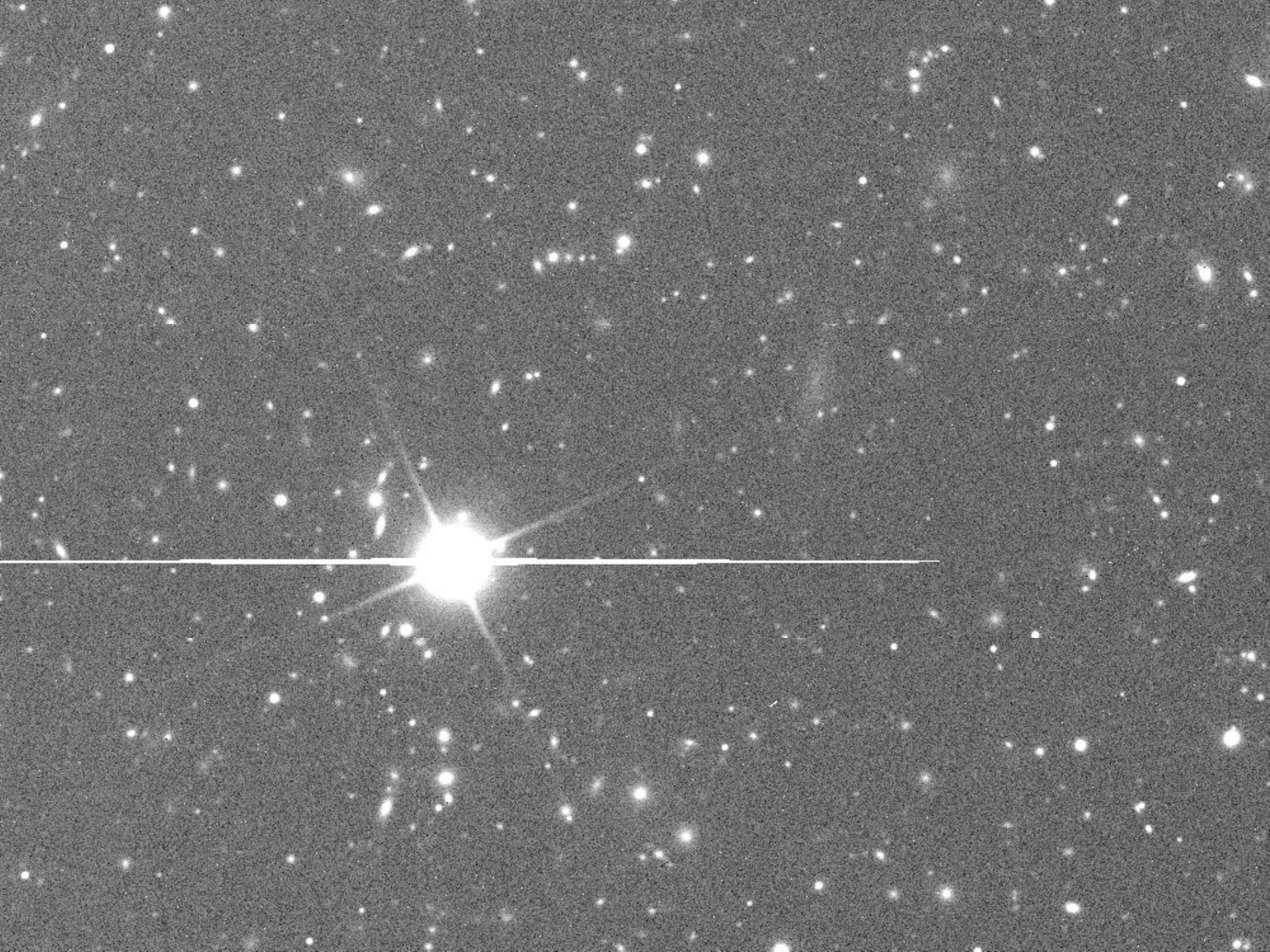
~1 sq. degree



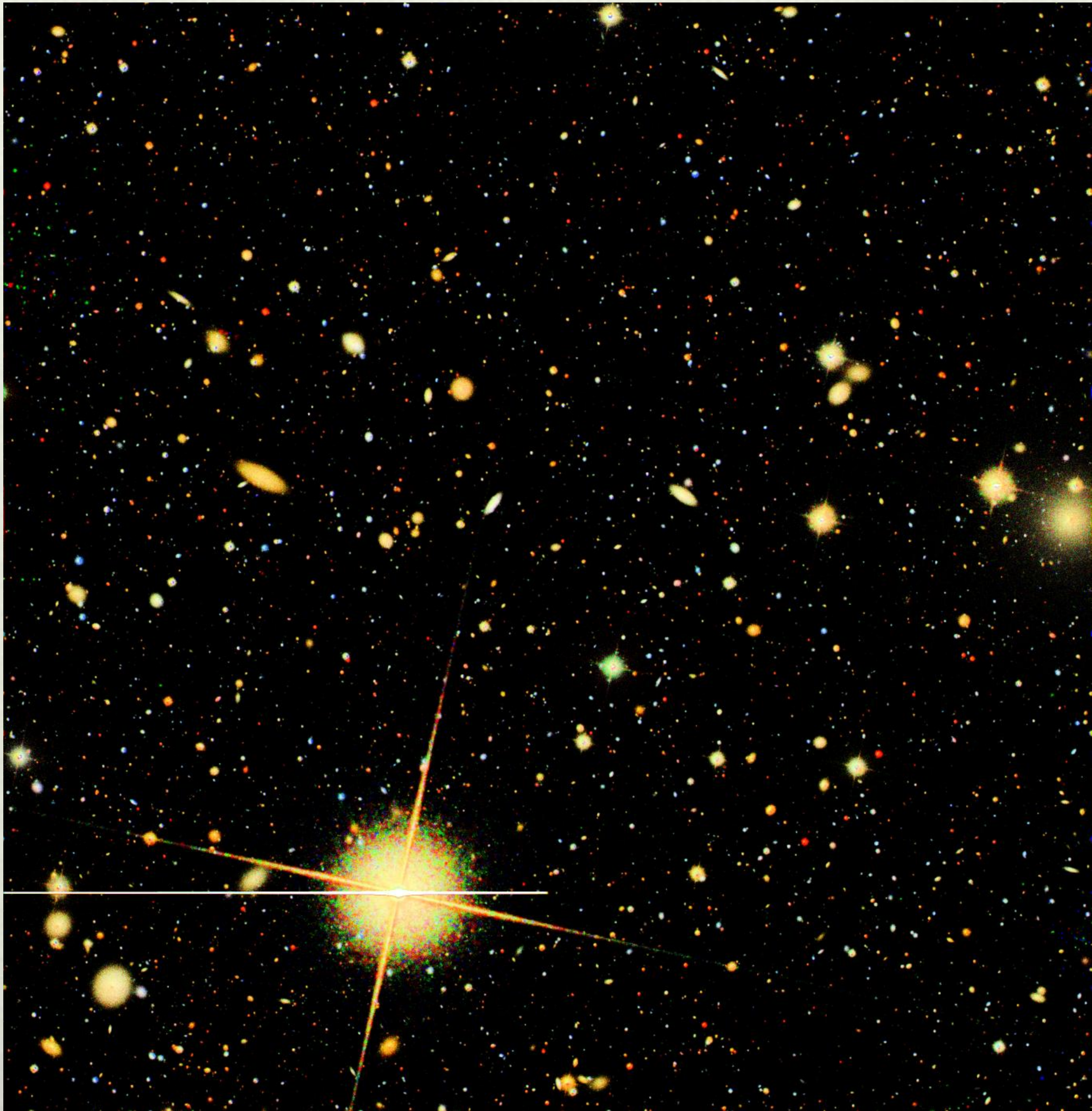
Central chip

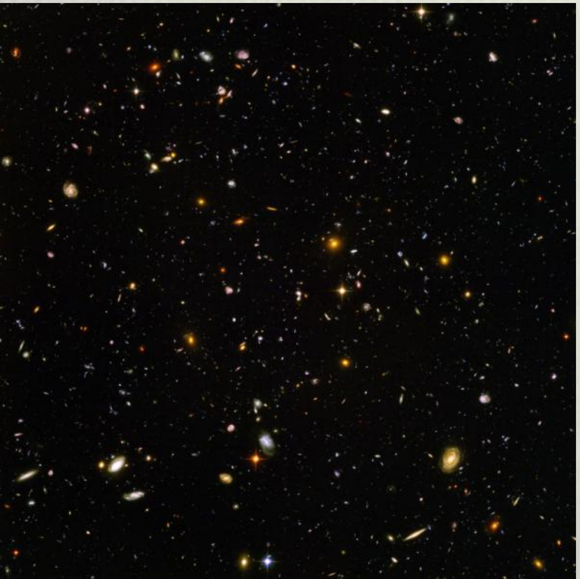
15’ x 15’





3 Color Image





4 Major LSST Data Challenges so far (4/09,6/10,9/10,5/11,4/12); Run on grid computing at Purdue (incl. OSG), UW, SLAC, and Google; Currently produce data at ~10% of real time; All analyzed by Data Management Pipelines

- 4 thousand visits
- 28 million amplifier images
- 44 billion astrophysical objects
- 4 quadrillion photons

Everything compared to simulation truth (not possible with real data)

Show all

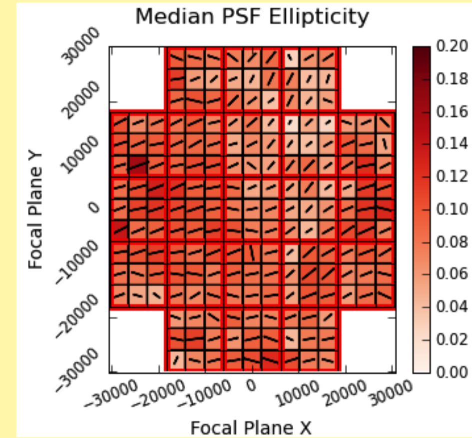


Figure 1.0: Median PSF Ellipticity
medPsfEllip.png: timestamp=2011-07_31 16:08:56

Show all

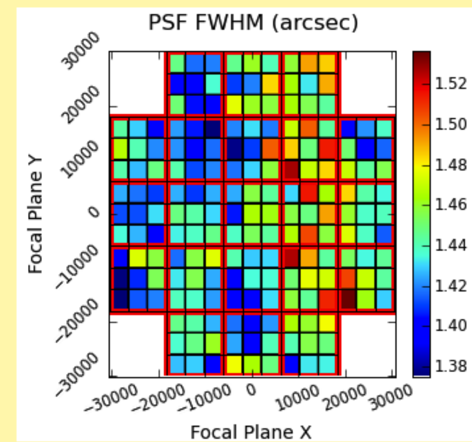
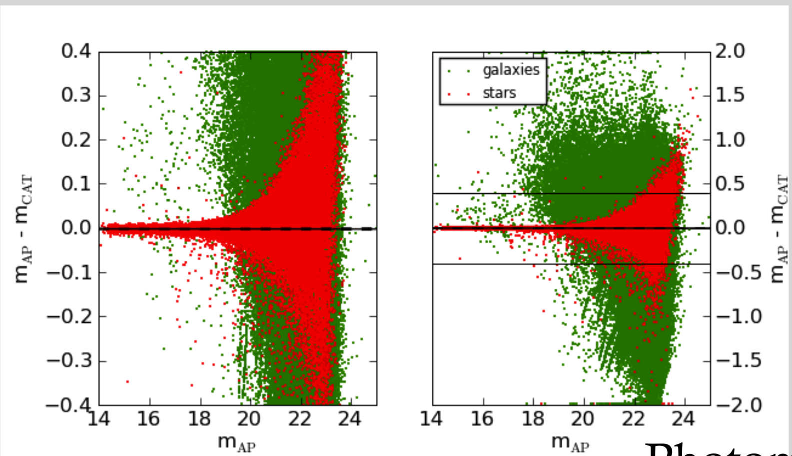
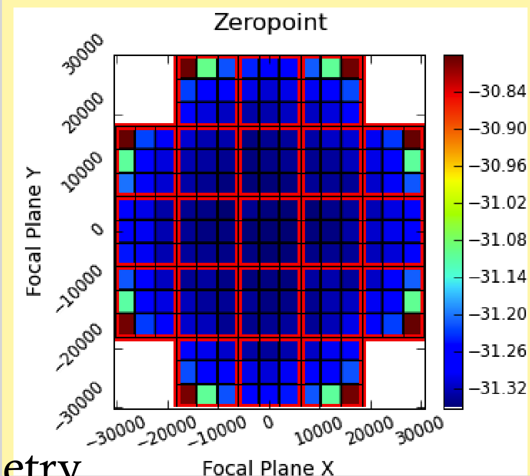
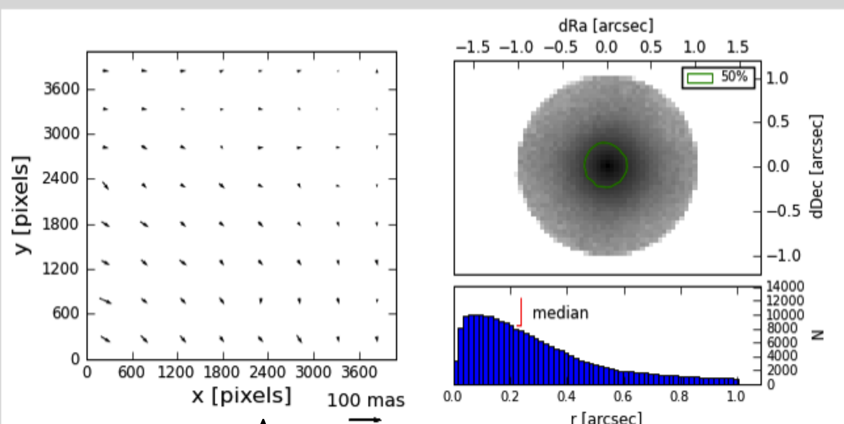


Figure 1.1: FWHM of Psf (arcsec)
psfFwhm.png: timestamp=2011-07_31 16:08:57

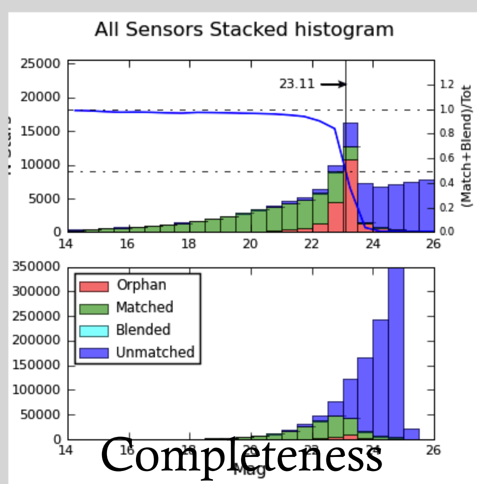




Photometry

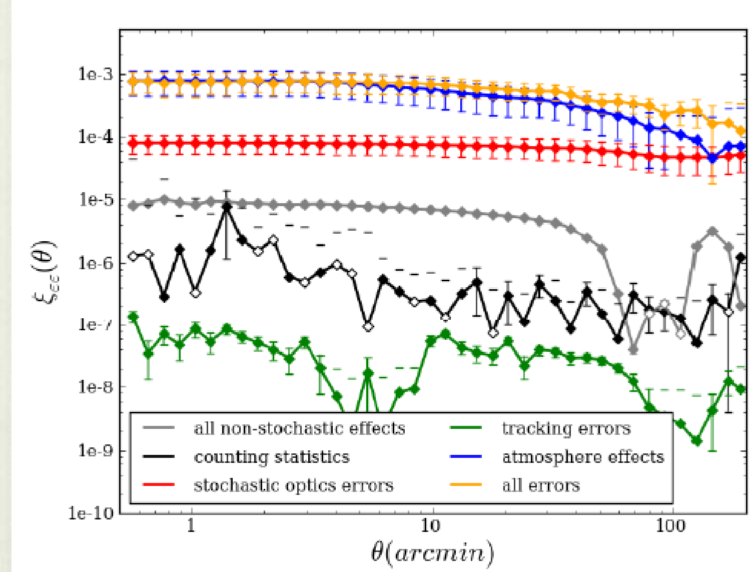


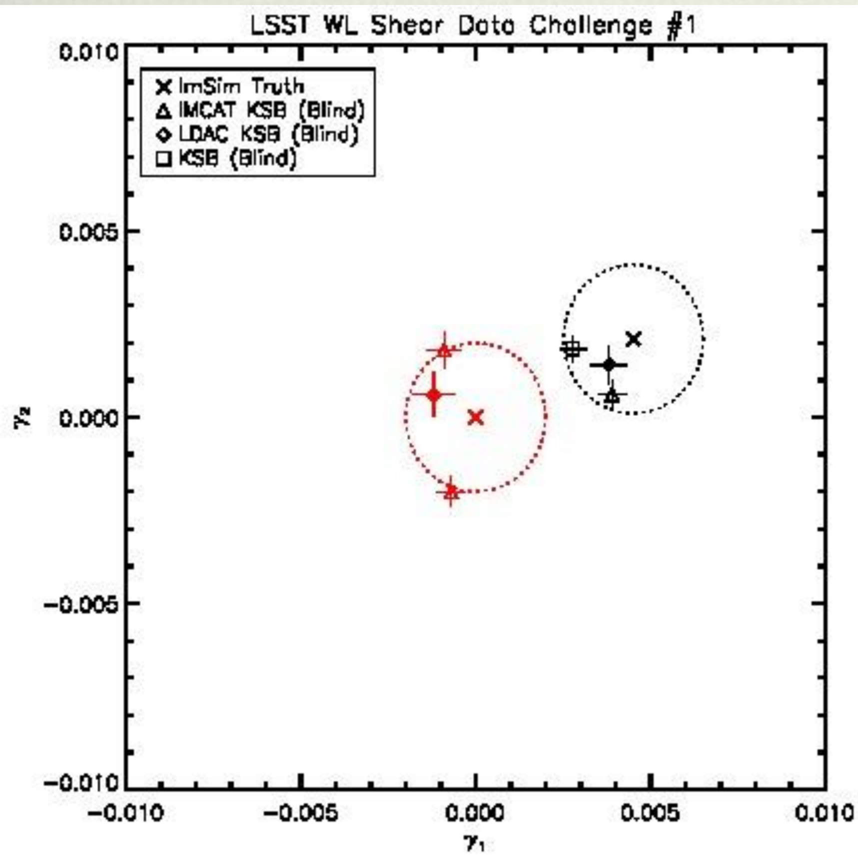
Astrometry

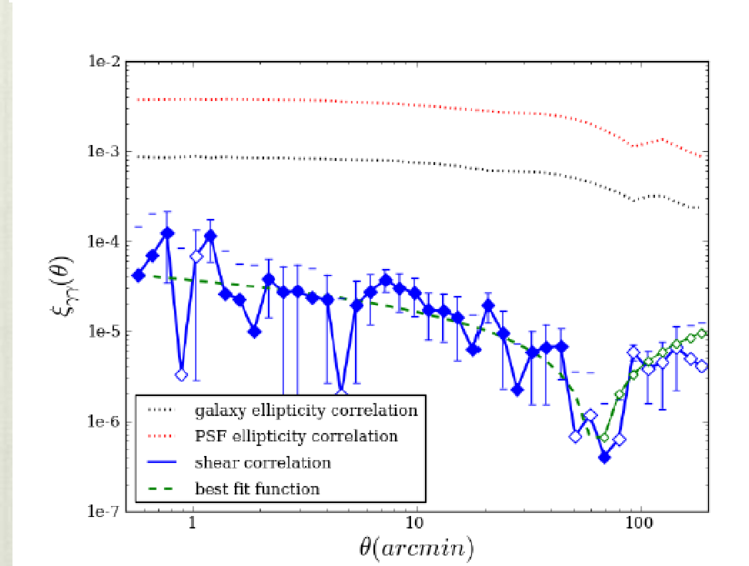


Completeness

PSF size & shape





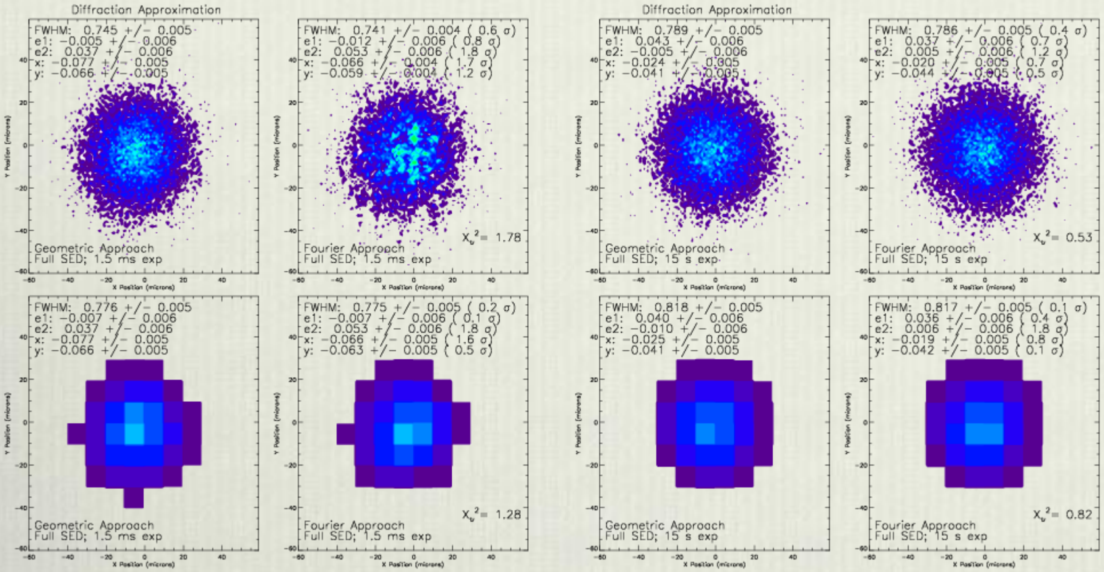


Chang et al. 2012

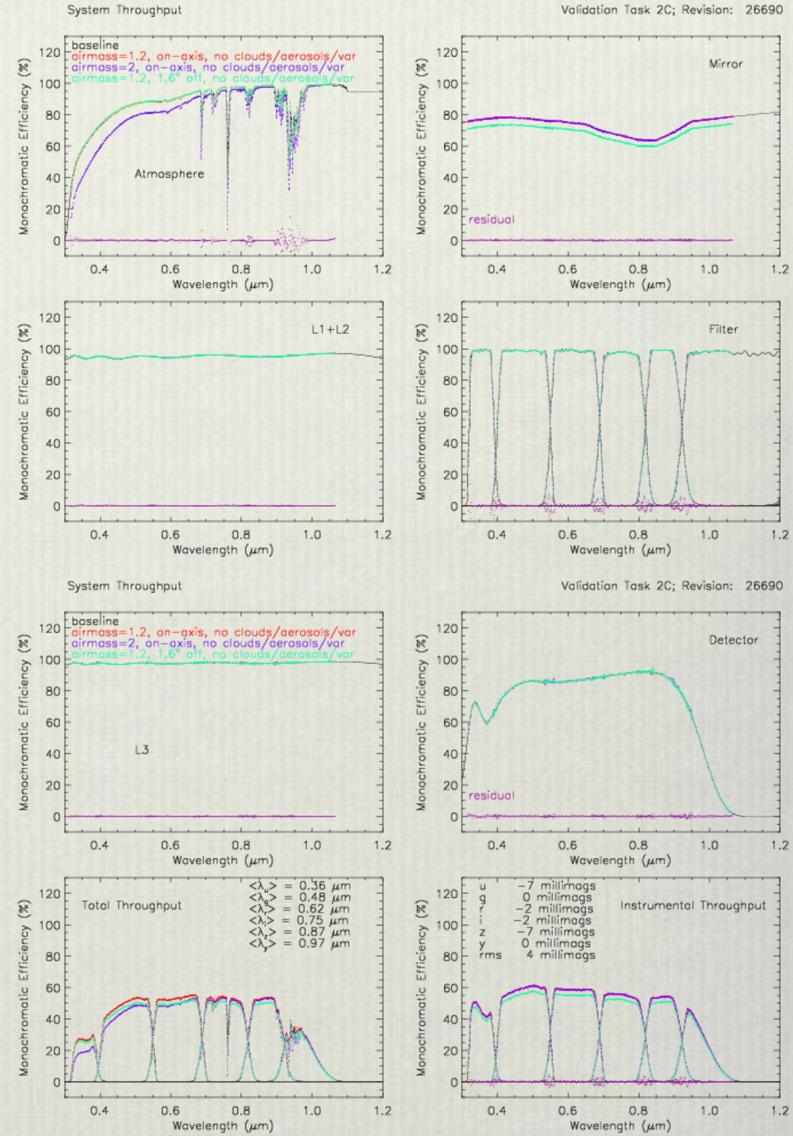
JRP, Bard, Allen, Li, Cui

- Blind shear survey with 10 sq. degrees
- Estimated shear systematic floor

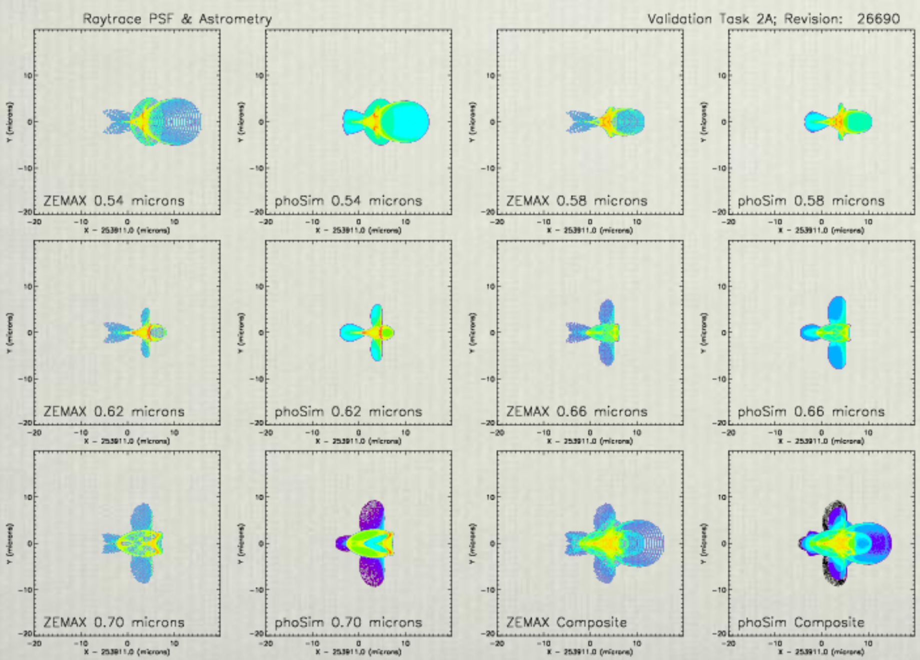
Validation!



Diffraction Approximation
FWHM: 0.745 +/- 0.005
e1: -0.005 +/- 0.006
e2: 0.037 +/- 0.006
x: -0.077 +/- 0.005
y: -0.066 +/- 0.005
Geometric Approach
Full SED; 1.5 ms exp
FWHM: 0.741 +/- 0.004 (0.6 σ)
e1: -0.012 +/- 0.006 (0.8 σ)
e2: 0.053 +/- 0.006 (1.8 σ)
x: -0.066 +/- 0.004 (1.7 σ)
y: -0.059 +/- 0.004 (1.2 σ)
Fourier Approach
Full SED; 1.5 ms exp
X_ν^2= 1.78
Diffraction Approximation
FWHM: 0.789 +/- 0.005
e1: 0.043 +/- 0.006
e2: -0.005 +/- 0.006
x: -0.024 +/- 0.005
y: -0.041 +/- 0.005
Geometric Approach
Full SED; 15 s exp
FWHM: 0.786 +/- 0.005 (0.4 σ)
e1: 0.037 +/- 0.006 (0.7 σ)
e2: 0.005 +/- 0.006 (1.2 σ)
x: -0.020 +/- 0.005 (0.7 σ)
y: -0.044 +/- 0.005 (0.5 σ)
Fourier Approach
Full SED; 15 s exp
X_ν^2= 0.53
FWHM: 0.776 +/- 0.005
e1: -0.007 +/- 0.006
e2: 0.037 +/- 0.006
x: -0.077 +/- 0.005
y: -0.066 +/- 0.005
Geometric Approach
Full SED; 1.5 ms exp
FWHM: 0.775 +/- 0.005 (0.2 σ)
e1: -0.007 +/- 0.006 (0.1 σ)
e2: 0.053 +/- 0.006 (1.8 σ)
x: -0.066 +/- 0.005 (1.6 σ)
y: -0.063 +/- 0.005 (0.5 σ)
Fourier Approach
Full SED; 1.5 ms exp
X_ν^2= 1.28
FWHM: 0.818 +/- 0.005
e1: 0.040 +/- 0.006
e2: -0.010 +/- 0.006
x: -0.025 +/- 0.005
y: -0.041 +/- 0.005
Geometric Approach
Full SED; 15 s exp
FWHM: 0.817 +/- 0.005 (0.1 σ)
e1: 0.036 +/- 0.006 (0.4 σ)
e2: 0.006 +/- 0.006 (1.8 σ)
x: -0.019 +/- 0.005 (0.8 σ)
y: -0.042 +/- 0.005 (0.1 σ)
Fourier Approach
Full SED; 15 s exp
X_ν^2= 0.82



System Throughput
Validation Task 2C; Revision: 26690
baseline
airmass=1.2, on-axis, no clouds/aerosols/var
airmass=2, on-axis, no clouds/aerosols/var
airmass=1.2, 1.6° off, no clouds/aerosols/var
Monochromatic Efficiency (%)
Wavelength (μm)
Atmosphere
Mirror
residual
L1+L2
Filter
System Throughput
Validation Task 2C; Revision: 26690
baseline
airmass=1.2, on-axis, no clouds/aerosols/var
airmass=2, on-axis, no clouds/aerosols/var
airmass=1.2, 1.6° off, no clouds/aerosols/var
L3
Detector
residual
Total Throughput
<λu> = 0.36 μm
<λg> = 0.48 μm
<λr> = 0.62 μm
<λi> = 0.75 μm
<λz> = 0.87 μm
<λy> = 0.97 μm
u -7 millimags
g 0 millimags
r -2 millimags
i -2 millimags
z -7 millimags
y 0 millimags
rms 4 millimags
Instrumental Throughput



Raytrace PSF & Astrometry
Validation Task 2A; Revision: 26690
ZEMAX 0.54 microns
phoSim 0.54 microns
ZEMAX 0.58 microns
phoSim 0.58 microns
ZEMAX 0.62 microns
phoSim 0.62 microns
ZEMAX 0.66 microns
phoSim 0.66 microns
ZEMAX 0.70 microns
phoSim 0.70 microns
ZEMAX Composite
phoSim Composite

Validation Summary for Revision: [illegible]

Validation Test	Validation Metric	Accuracy or Value	P/F (Tolerance)
UNIT TESTS:			
find	Function Return Value		Pass
findLinear	Function Return Value		Pass
findLinearWrap	Function Return Value		Pass
normalize	Function Return Value		Pass
interpolate	Function Return Value		Pass
interpolateLinear	Function Return Value		Pass
interpolateBilinear	Function Return Value		Pass
interpolateBilinearFloatWrap	Function Return Value		Pass
refined	Function Return Value		Pass
refract	Function Return Value		Pass
propagate	Function Return Value		Pass
			UNIT TEST SUMMARY: 11 Pass and 0 Fa[illegible]
INTEGRATION TESTS:			
1A Diffraction Approximation	Integrated PSF Comparison	1.17 (10^4/sec^2)	Pass (< 3.00)
	FWHM error	0.000 arcsec	Pass (< 0.01)
	Sqrt(ellip)*FWHM error	0.000 arcsec	Pass (< 0.00)
	Centroid error	0.001 arcsec	Pass (< 0.01)
	Instantaneous Monochr PSF Comparison	1.84 (10^4/sec^2)	Pass (< 3.00)
	FWHM error	0.000 arcsec	Pass (< 0.01)
	Sqrt(ellip)*FWHM error	0.000 arcsec	Pass (< 0.00)
	Centroid error	0.01 arcsec	Fail (< 0.01)
	Instantaneous Full SED PSF Comparison	8.18 (10^4/sec^2)	Pass (< 3.00)
	FWHM error	0.000 arcsec	Pass (< 0.01)
	Sqrt(ellip)*FWHM error	0.000 arcsec	Pass (< 0.00)
	Centroid error	0.01 arcsec	Fail (< 0.01)
1B Screen Convergence	PSF FWHM Error	0.00 arcsec	Pass (< 0.01)
	PSF Centroid Error	0.00 arcsec	Pass (< 0.01)
	PSF Sqrt(Ellip)*FWHM Error	0.00 arcsec	Pass (< 0.01)
1C Cubic at Sizes	Atm X=1 PSF size	0.60 arcsec	Pass (0.60 +/- 0.08)
	Average Ellipticity	0.08	Pass (< 0.05)
	Stdev Ellipticity	0.01	Pass (< 0.03)
	Ellipticity Decorrelation Length	3.00 degrees	Pass (> 0.03)
	Avg Diff Astrometry, 3 arcmin	8.06 milliarcsec	Pass (< 10.00)
	Stdev Diff Astrometry, 3 arcmin	1.18 milliarcsec	Pass (< 0.00)
	Atm X=2 PSF size	0.70 arcsec	Pass (0.80 +/- 0.08)
	Average Ellipticity	0.05	Pass (< 0.05)
	Stdev Ellipticity	0.08	Pass (< 0.03)
	Ellipticity Decorrelation Length	10.30 degrees	Pass (> 0.03)
	Avg Diff Astrometry, 3 arcmin	3.08 milliarcsec	Pass (< 10.00)
	Stdev Diff Astrometry, 3 arcmin	8.14 milliarcsec	Pass (< 0.00)
	Atm+Opt PSF size	0.12 arcsec	Fail (0.00 +/- 0.08)
	Average Ellipticity	0.08	Pass (< 0.10)
	Stdev Ellipticity	0.05	Pass (< 0.10)
	Ellipticity Decorrelation Length	3.10 degrees	Pass (> 0.08)
	Avg Diff Astrometry, 3 arcmin	8.31 milliarcsec	Pass (< 10.00)
	Stdev Diff Astrometry, 3 arcmin	1.27 milliarcsec	Pass (< 0.00)

Validation Summary for Revision: 26080

Validation Task	Validation Metric	Accuracy or Value	P/F (Tolerance)
1B Star Trails	Avg 1-D astrometric shift below 18m mag	0.014 arcsec	Pass (0.02 +/- 0.01)
	Stdev 1-D astrometric shift below 18m mag	0.018 arcsec	Pass (0.01 +/- 0.01)
3A Spot Diagrams	Spot Diagram Overlap	97.8846 overlap	Pass (> 95.00)
	PSF FWHM error	0.12 microns	Pass (< 0.30)
	Sqrt(ellip)*FWHM error	0.03 microns	Pass (< 0.30)
	Centroid error	0.12 microns	Pass (< 0.30)
3B Instrumental PSF Properties	Total non-atm PSF size	0.491 arcsec	Fail (< 0.28)
	Optics Design	0.118 arcsec	Fail (< 0.100)
	Internal Seeing	0.081 arcsec	Pass (< 0.08)
	Perturbations/Misalignments	0.377 arcsec	Fail (< 0.298)
	Charge Diffusion	0.390 arcsec	Fail (< 0.298)
	PSF Sqrt(ellip)*FWHM	0.18 arcsec	Pass (< 0.21)
	Optics Design	0.07 arcsec	Pass (< 0.21)
	Internal Seeing	0.04 arcsec	Pass (< 0.21)
	Perturbations/Misalignments	0.17 arcsec	Pass (< 0.21)
	Charge Diffusion	0.00 arcsec	Pass (< 0.21)
	PSF Centroid	0.30 arcsec	Pass (< 1.400)
	Optics Design	0.00 arcsec	Pass (< 1.400)
	Internal Seeing	0.01 arcsec	Pass (< 1.400)
	Perturbations/Misalignments	0.30 arcsec	Pass (< 1.400)
	Charge Diffusion	0.00 arcsec	Pass (< 1.400)
3C Throughput	Avg band flat AB_{zero} zeropoint	4.06 millimags	Pass (< 20.00)
	u flat AB_{zero} zeropoint	27.72 mags	Pass (27.72 +/- 0.20)
	g flat AB_{zero} zeropoint	30.70 mags	Pass (30.70 +/- 0.20)
	r flat AB_{zero} zeropoint	30.75 mags	Pass (30.74 +/- 0.20)
	i flat AB_{zero} zeropoint	30.60 mags	Pass (30.60 +/- 0.20)
	z flat AB_{zero} zeropoint	30.32 mags	Pass (30.31 +/- 0.20)
	y flat AB_{zero} zeropoint	27.08 mags	Pass (27.09 +/- 0.20)
	RMS Atm Transmission Error	25.50 millimags	Pass (< 30.00)
3D Spider Diffraction	Error in Power in diag. cross. spikes	0.5006	Pass (< 0.30)
3A Camera Defects	ADC Histogram KS p-value	100.0006	Pass (< 100.00)
3E Charge Diffusion	Diffusion size at 100 microns	15.11 microns	Pass (12.00 +/- 3.00)
4A Chip w/ Stars and Galaxies	Total simulation time	138.50 minutes	Pass (< 300.00)
	Unexpanded simulation rate	332 kphotons/s	Pass (> 100.00)
	Dark Sky Speed Factor	43	Pass (> 1.00)
	m=12 Speed Factor	7	Pass (> 1.00)
4B Galaxy w/ Dyn Trans on/off	Color Flux Accuracy	0.1356	Pass (< 0.15)
4C m=12 Star Opt on/off	PSF Comparison	309.30 (X^2/dof)	Fail (< 3.00)
4D Corner chip Block Opt on/off	PSF Comparison	1.05 (X^2/dof)	Pass (< 3.00)

INTEGRATION TEST SUMMARY: 34 Pass o

Conclusions

- Have a multi-purpose high fidelity optical image simulator (PhoSim) with physics appropriate for optical survey telescopes
- Will enable a number of state-of-the art algorithms to be developed that necessary for high precision cosmological measurements in the LSST DESC
- LSST will enable dark energy properties to be measured in unprecented detail & will make dark matter map of the entire sky
- Also possible to use for other telescopes